

Rajni Rajan
Faheem Ahmad
Kuldeep Pandey *Editors*

Innovations in Climate Resilient Agriculture

 Springer

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ISBN 978-3-031-84801-8 ISBN 978-3-031-84802-5 (eBook)
<https://doi.org/10.1007/978-3-031-84802-5>

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Foreword

Agriculture has always been at the mercy of nature. From ancient times to the present day, farmers have faced droughts, floods, storms, and other natural adversities. However, the current challenge to agriculture is unprecedented in its scope and urgency: climate change. The changing climate threatens to upset the delicate balance on which agricultural systems rely, jeopardizing food security, livelihoods, and ecosystems.

As the impacts of climate change intensify, the concept of climate-resilient agriculture has moved from the periphery of agricultural discourse to its centre. This book is a timely contribution to that critical discussion. It highlights the urgent need to transform our agricultural practices, making them more adaptable to the changing climate, while also reducing agriculture's own contributions to climate change. Through a combination of innovative techniques, traditional knowledge, and policy interventions, climate-resilient agriculture aims to safeguard our food systems against the unpredictable challenges ahead.

This book brings together a wealth of knowledge from experts who understand the complexity of the problem and the need for holistic solutions. It explores the science behind climate impacts, examines successful case studies from around the world, and offers practical strategies for implementation. From precision agriculture and spatial technologies to robotics, hydroponics, and molecular techniques, the topics covered here provide a comprehensive road map for farmers, researchers, policymakers, and all stakeholders committed to building a more sustainable and resilient future.

Reading this book will not only give you a deeper understanding of the challenges we face but also a sense of optimism. The path to climate resilience in agriculture is not without its difficulties, but it is achievable. It requires a collective effort, innovative thinking, and a commitment to long-term sustainability. As you turn the pages, I encourage you to consider how you can contribute to this vital endeavour, ensuring that agriculture continues to thrive in harmony with our changing planet.

This is not just a book about agriculture; it is a call to action. We must act now, and the knowledge within these pages serves as a crucial tool for this action. Together, we can build a future in which agriculture not only survives but thrives in the face of climate change, providing food security for generations to come.

Deputy Director General (Horticulture)
New Delhi, India
28/08/2024

S. K. Singh

Preface

The world stands at a critical juncture, where the effects of climate change are increasingly palpable, challenging the sustainability of global agricultural systems. As the climate continues to shift, so too must our strategies for ensuring food security and agricultural resilience. This book, *Innovations in Climate Resilient Agriculture*, is a response to this urgent need, presenting a comprehensive exploration of the innovative practices, technologies, and scientific advancements that are essential for building a resilient agricultural future.

This book is born out of a recognition that traditional agricultural practices are no longer sufficient to meet the demands of a rapidly changing environment. Climate-smart farming, the foundation of this volume, represents a paradigm shift in how we approach food production. It emphasizes the integration of new technologies, innovative practices, and sustainable principles to create agricultural systems that are not only productive but also resilient to the vagaries of climate change.

The chapters in this book explore a wide array of groundbreaking innovations. The first part delves into AI-powered strategies that are revolutionizing the way we manage crops, providing farmers with tools to anticipate and mitigate climate-related stresses. These technologies, coupled with breeding interventions, are crucial in developing crop varieties that can thrive under adverse conditions.

As we move further into this book, the focus shifts to the molecular level, where advanced mutagenesis, gene mapping, and high-throughput sequencing are unlocking new possibilities for crop improvement. These approaches are helping to identify and propagate traits that enhance resilience, ensuring that crops can withstand the challenges posed by extreme weather events and shifting growing conditions.

Nanotechnology, genome editing, and biotechnology are explored as powerful tools in the arsenal of climate-resilient agriculture. These technologies offer unprecedented precision in enhancing crop performance and adaptability, making it possible to engineer plants that are better equipped to survive and flourish in a changing world.

This book also highlights innovative cultivation techniques, such as hydroponics, aeroponics, and protected environment farming, which are transforming how and where we grow food. These methods not only conserve resources but also offer

solutions for farming in regions where traditional agriculture is no longer viable. Spatial technologies, robotics, and UAVs represent the frontier of climate-smart agriculture, bringing precision and efficiency to farming practices. By integrating these tools into crop systems, we can create more resilient and sustainable agricultural landscapes. Finally, the importance of sustainable post-harvest practices is addressed, ensuring that the benefits of these innovations extend beyond the field and contribute to the overall resilience of the agricultural value chain.

Innovations in Climate Resilient Agriculture is a testament to the power of human ingenuity and scientific progress. It is a call to action for all those involved in agriculture—researchers, policymakers, and farmers—to embrace these innovations and work together to build a resilient future. As we confront the challenges of climate change, this book provides the knowledge and tools necessary to ensure that our agricultural systems are not only sustainable but also capable of thriving in the face of adversity.

Phagwara, Punjab, India
Aligarh, UP, India
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Chapter 1

Climate-Smart Agriculture and the Future of Agriculture



Arianna Latini

1.1 Background

In all regions of the world there is significant evidence of challenges enhancement in agriculture. On one side, the developed world is troubled and busy with the management of structural changes in rural areas; on the other side, the world population is increasing (projected to reach 10 billion by 2050), causing a clear concern in the developing parts of the world. This sharp contrast becomes even more serious due to the currently observable negative impacts on farmers worldwide, with more dramatic consequences for the poorest regions where the population relies exclusively on agriculture.

To protect food security globally in the future, digitalization and its related technology-enabled solutions, the so-called smart farming solutions, can provide support to agriculture and agroindustry, making them more sustainable and efficient in the utilization of resources. FAO defines climate-smart agriculture (CSA) as “an approach that helps guide actions to transform agri-food systems toward green and climate resilient practices,” in line with the Paris Agreement on Climate Change and the 2030 Agenda including the Sustainable Development Goals (SDGs). Moreover, “it aims to tackle three main objectives: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible” (Fig. 1.1). At the same time, CSA is at the base of a global agrifood system that must feed the world, combining the possibilities offered by innovation with the need to rethink production in order to manage all resources more efficiently reducing their extreme exploitation (FAO, 2017, 2021a).

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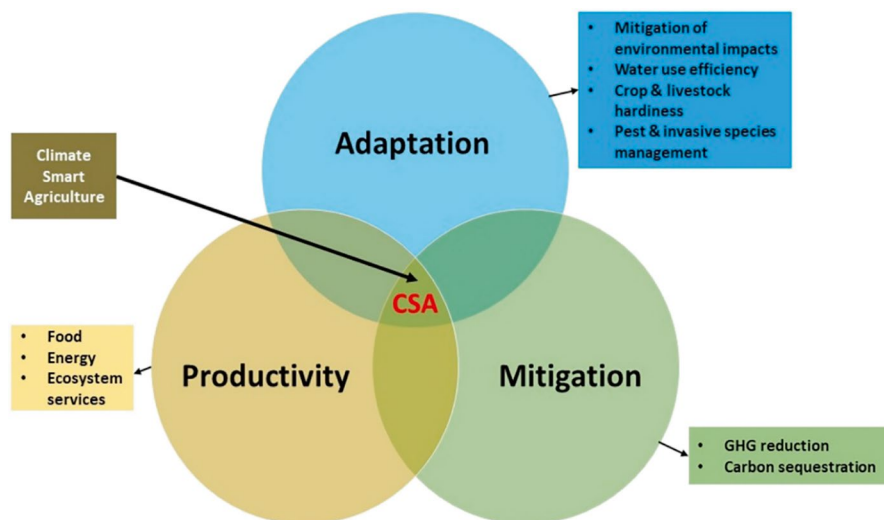


Fig. 1.1 Climate-smart agriculture (CSA) components. Proceeding from Jariwala et al., (2022)

CSA supports the FAO Strategic Framework 2022–2031 based on the *Four Betters*: better production, better nutrition, a better environment, and a better life for all, leaving no one behind (FAO, 2021b). A CSA practice is context-specific and depends on local socioeconomic, environmental, and climate change factors. FAO recommends the approach be implemented through five action points: expanding the practical application of CSA research findings, supporting enabling policy frameworks, reinforcing territorial institutions, enhancing funding and different funding options, and applying CSA practices in the field.

In Italy, for example, the spread of new technologies that meet supply chain players, smart agrifood and blockchain, has led the agrifood sector—which constitutes an increasingly important part of the Italian economy—to a deep transformation. These technologies, such as the Internet of Things (IoT) and Artificial Intelligence (AI), can make a difference and contribute to the further evolution of this sector, driving it towards Agrifood 4.0. The organization is revolutionizing itself and new technologies are becoming enablers of new synergies in the agrifood sector. The opportunities for businesses are many: the possibility of collecting updated information and data, real-time control of goods, time synchronization between production and sale, as well as making supply chain management more efficient in a more sustainable conscious ecosystem. Agriculture 4.0 innovations, in the peninsula, are increasingly perceived as a way to deal with the damage caused by climate change, and according to national statistical data, they continue their growth trajectory despite credit crunch and economic difficulties. Importantly, the counterbalance is that only those agrifood cooperatives and companies which had already invested capital in technological innovation were the main investors continuing with the investment. This may be better explained by the numbers reported by the Smart

AgriFood Observatory of the Politecnico di Milano and the University of Brescia (<https://www.osservatori.net/en/research/active-observatories/smart-agrifood>, last accessed on July 15, 2024): in 2023, Agriculture 4.0 reached a turnover of 2.5 billion, which was 19% higher than in 2022; only 8% in 2022 and 9% in 2023 of Italian agricultural surfaces were cultivated with digital technologies. Interestingly, the type of investments has shifted from agricultural machines and their monitoring systems to software for management solutions and FMIS (Farm Management Information Systems) and mapping systems for crops and land.

The agrifood sector is getting closer and closer to the needs of both producers and consumers. Digitalization plays an important role at both ends of the supply chain: consumers—with services for information on product traceability or on the state of conservation and freshness—and agricultural companies, with Agriculture 4.0 solutions for remote mapping and monitoring of crops or agricultural machinery, and for business management. The importance of data is becoming more and more central, and the agrifood sector is looking with strong interest at blockchain technologies, but it will be necessary to increase the digital culture and trust in the potential of these technologies.

Not only agriculture is witnessing an evolution in demand towards a healthier and more sustainable diet, even with an increased attention to the potential of personalized nutrition, but the consciousness of digital technologies and their potential is also growing. Indeed, if correctly implemented and inserted into a strategic digital transformation plan, they can aid the development of innovative services and related products, as well as new models of business. In this context, ecosystems play a crucial role in the interaction among the stakeholders of the agricultural sector and the whole agrifood system. Nowadays, for example, thanks to pervasive innovations and the spread of digital platforms such as those for e-commerce, farmers themselves, to a certain extent regardless of their size, can create a more direct relationship with final consumers, in a logic of short supply chain and, in some cases, of direct consumer contact with the territory and local productions. Digitalization and Industry 4.0, as well as new consumer expectations, represent therefore drivers of an agrifood ecosystem model, encouraging the creation and valorization of new partnerships and collaboration models within the supply chains and the sector.

At the local level, the operational characteristics and technologies of CSA are still under definition being dependent on the relationships among productivity, adaptation, and mitigation (FAO, 2017). In this regard, CSA attitude can be considered knowledge-intensive and needs support from both policymakers and farmers. The farmers themselves and main stakeholders are requested to analyze and recognize the more adaptable climate-smart technologies in the context of the land physical-chemical and agricultural features, and socioeconomic traits of their countries/regions; moreover, policymakers and academics have to support local small-holder farmers to upscale CSA in developing and underdeveloped countries (Ogunyiola et al., 2022). Anyway, the agricultural practices of CSA have been fostered and progressed thanks to a growth in specific strategies and action plans, policies, partnerships, and investments at the global level (Dinesh et al., 2017). Different studies prove that the CSA approach is potentially able to sustain food production

to feed the world under the negative scenarios due to climate changes, including ensuring food security, while, at the same time, limiting greenhouse gas (GHG) emissions; of course, to achieve these goals, wide global implementation of related agricultural strategies, technologies, and agronomic tools is required (Hussain et al., 2022; De Pinto et al., 2020).

With respect to carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) have lower emissions but at the same time present a higher global warming potential (GWP), respectively, 296 and 34 times greater than that of CO_2 (Huang et al., 2018). Therefore, for a correct evaluation of the overall GWP of GHGs, it is necessary to compute the effects of agricultural management on CH_4 and N_2O emissions (Stocker et al., 2013). Most N_2O emissions into the atmosphere are linked to the agricultural use of nitrogen fertilizers. Knowledge of the phenomenon has brought research attention towards the study of more sustainable practices, limiting the use of chemical fertilizers, that are at the same time capable of maintaining high crop productivity.

CSA technologies, practices, and strategies may sustain producers to increase sustainability and agricultural activity, together with their income, while both mitigating and adapting to climate changes. In this chapter, the benefits and the techniques of CSA will be reported and discussed, with an attempt to delineate a possible alternative sustainable future of agriculture, even though several limitations need to be overcome, and the specific practices and technologies should be applied with conscience and a good knowledge based on the geographical-climatic and environmental location and on the specific agricultural production system, also in reference to the crop species and to the crops farmed. The second section of this chapter focuses on the technologies suggested for the practice of smart climate and more resilient agriculture.

1.2 CSA Technologies

The climate-smart agriculture (CSA) approach embraces a large panel of technologies, from the practice of conservation minimizing mechanical soil disturbance up to the introduction of novel cultivable species and improved germplasm lines with useful genetic traits facilitating plant resistance to biotic and abiotic stresses. Also, integrated pest management (IPM) as an environmentally sensitive way for pest control, the introduction of renewable energy sources and energy efficiency in the agriculture and agrifood sectors, the protection of the key natural resources such as water and soil, and the implementation of information and communication technologies (ICTs) and digitalization of various farming operational processes represent relevant topics linked to specific CSA and technologies (Fig. 1.2). The whole panel of technologies is quite huge, and in this chapter, only some of them have been selected and discussed in major detail.

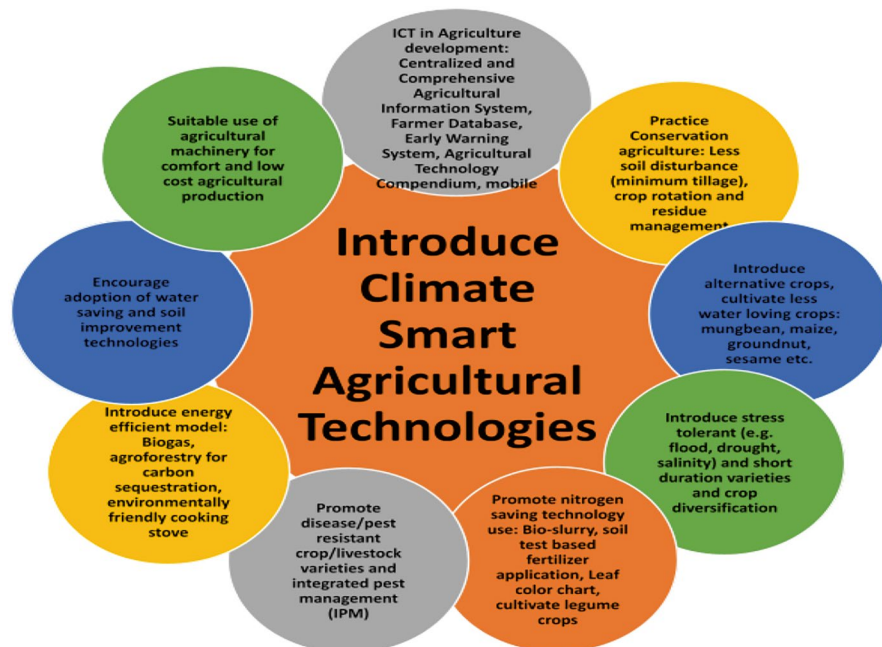


Fig. 1.2 Climate-smart agriculture (CSA) technologies. Proceeding from <https://bracinternational.org/wp-content/uploads/2021/08/our-climate-smart-strategy.pdf>

1.2.1 Agrometeorological Applications

Changes in temperature and rainfall, extreme weather situations as for example days with a particular and not usual high humidity level, long dry spells, high night temperature excursions, and heatwaves, but also drought, flood, pests and diseases represent the evident symptoms of climate change. Agricultural meteorology, namely, agrometeorology or Agromet, focuses on weather and climate effects on agriculture, by exploiting useful indications from microclimate and other environmental parameters. The proper knowledge of climate and weather processes, together with the knowledge of agricultural systems, supports agrometeorologists in estimating the effects of their changes in crop productivity and sustainability at the different levels, from the local up to the regional and national ones. Prior information on weather conditions and their probable effect on the agriculture sector may be useful to farmers to face challenges, safeguard their crops, and/or minimize crop damage (Bacci et al., 2020). Goals of agrometeorology in the field of CSA include the development of advisories that use climate parameters as triggers for selection between alternative farm intervention that may optimize production and sustainability of the systems (climate-based solutions); the awareness of carbon and water footprint of the specific agriculture and agrifood systems; and the creation of communities and networks of researchers, meteorologists, agronomists, farmers, and

other knowledge providers, together with politicians and various stakeholders. Overall, through these goals, agrometeorology aims to bring operational science-based support tools and innovation to farmers. Among the provided benefits, the use of meteorological information locally available or directly measured in the field, connected to the specific farming system, may generate warnings in agrometeorological applications that can help to enhance productivity by avoiding the potential loss because of a weather/climate unexpected event. A climate service (CS) can be defined as scientifically based information and products that increase users' knowledge and understanding about the impacts of climate on their decisions and actions (Tall et al., 2018). The use of CS for provisioning information to achieve an informed decision-making about adaptation actions to afford has gained momentum (Ofogebu & New, 2022), to the point that agrometeorology not only is of support in improving yields but also in lessening the negative effects of fertilizers and pesticides used for pest and disease control.

1.2.2 No Tillage

In relation to the tillage practice (mechanical processing of the agricultural soil), the main approach in traditional agriculture is conventional tillage (CT), while no tillage (NT), involving the total absence of mechanical tillage, with minimum or no soil disturbance, represents its sustainable counterpart choice. NT is often applied in combination with other agricultural practices such as residue retention, crop rotation, and cover crops (CC).

It is well known that tillage system affects GWP and that NT practice has the potential to reduce GHG emissions and increase crop yields, improving food security and augmenting agroecosystem resilience to climate change. In their meta-analysis of 90 scientific manuscripts, Huang et al. (2018) assessed the NT effects with respect to conventional tillage (CT) on crop yields, GHG emissions, and GWP in cereal cropping systems. As a result, NT reduced GHG emissions and increased cereal yield in dry climates, but not in humid climates, and reduced GWP with acidic soils. In another study, the observation of the trends of N₂O emission in rain-fed Mediterranean agroecosystems, over a period of 18 years, resulted in an overall emission reduction of 2.8–3.3 times lower under NT compared to CT, demonstrating that for non-irrigated cultivations in Mediterranean area NT can be a win-win strategy for the equilibrium between agricultural productivity and low soil N₂O emissions (Plaza-Bonilla et al., 2018).

NT was proposed as a method to protect natural resources, in particular, soil from erosion and water from waste; thus, it is considered a good strategy for climate change adaptation of agricultural systems. As mentioned above, soil cover treatments are often implemented in croplands managed without tillage, thus organic matter and the carbon it contains accumulate in the topsoil (about 10 cm). Indeed, below the topsoil, neither an increase nor a decrease in carbon soil is detected, meaning that NT does not contribute to carbon sequestration. Anyway, observations

and experimental data on soil organic carbon (SOC) sequestration and NT are still contrasting, depending on climate and geographic characteristics (Baiaamonte et al., 2022). For example, in a simulation study under climate change for assessing synergistic effects of NT and CC on soil carbon dynamics in a long-term maize cropping system, NT increased SOC stocks with respect to CT, and, taken together, NT and CC practices effectively enhanced C sequestration (Huang et al., 2020).

1.2.3 Cover Crop Treatments

Cover crops (CCs) are nonproductive crops cultivated between the harvesting of one cash crop and the sowing of the next. Among their several functions, they provide numerous ecosystem services: they are capable of absorbing nitrates reducing their leaching, supply organic substance to the soil, improve soil physicochemical properties and microbial communities, reduce soil losses due to erosion, are effective in the control of weeds, and offer a beneficial habitat for insects. The containment of weeds is achieved because of the competition between weeds and CCs for space, water, and nutrients but also due to the allelopathic action of some species (Fernando & Shrestha, 2023). The application of CCs represents a key practice benefiting both soil and water conservation (Zhang et al., 2023). As NT, also CC treatment influences the GWP. The combination of these agronomic-environmental benefits determines economic advantages often difficult to quantify especially in the short term. However, in the medium-long term, the improvement of the soil structure and its nutrient and organic substance content can allow a reduction in the need for soil mechanical processing and a lower use of fertilizers.

There are also some critical issues that should be considered in CC treatments for sustainable vegetable production. CCs use water and could reduce groundwater recharge depending on how they are managed (Meyer et al., 2019). Another issue is that climate warms, and the production of some cool season vegetables could shift from summer (being too hot) to winter (becoming increasingly mild), leaving less fallow land available for winter cover cropping. A third potential challenge has to do with the availability of CC seeds due to the increased demand and limited supply (Brennan, 2017).

1.2.4 Integrated Soil Fertility Management

Integrated soil fertility management (ISFM) is defined as “A set of soil fertility management practices that necessarily include the use of fertilizers, organic inputs and improved germplasm, combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing the agronomic use efficiency of applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles” (Vanlauwe et al., 2010). In general, this

agricultural practice embraces a combination of chemical fertilizers with crop residues and manure or compost, favoring the application of locally available biological soil amendments, such as lime and biochar. To preserve the organic substances in soil, the use of natural organic soil improvers is suggested, often in combination with more conservative agricultural practices; such organic matter inputs exhibit multiple functional characteristics besides nutrient fertilization, for example, the control of pests (Latini et al., 2021).

For achieving an innovative, functional, and effective ISFM, it is necessary to consider farmers' priorities and needs. Indeed, farmers are required to intensify their agricultural strategy, and this can be embraced when they are tied to both input and output markets because they are more inclined to make investments that can certainly bring good profits. For example, in this perspective, the agricultural production encompassed up to now by ISFM, mainly represented by staple crops which are less profitable, should prefer the cultivation of novel and more elite crops and vegetables, ensuring farmers an economic return for their investments in fertilizers, organic matter inputs and amendments, selected suitable seeds, etc. For this reason, it is very important to listen to and then analyze the needs of the producers, also at the socioeconomic level, to direct them towards the best choice, planning, and implementation of their agricultural system.

1.2.5 Alternate Wetting and Drying

Alternate wetting and drying (AWD) is a water-saving and eco-friendly technology. In this practice, the flooding is repeatedly interrupted during the season, and water declines as the upper soil layer dries out before subsequent reflooding. In rice cultivation, which in general requires up to 3–5 times more water with respect to other cereals, AWD can be applied to reduce water use in irrigated fields. With respect to the conventional continuously flooded system (CF) used in rice production, which necessitates very large amounts of water and puts at severe risk the ecosystem due to GHG emission and accumulation in rice grains of heavy metals, such as arsenic (As) and mercury (Hg), AWD limits considerably these undesirable consequences (Ishfaq et al., 2020). Rice production is a major source of GHG emissions, particularly CH₄ emissions originating from the flooded fields, and AWD can substantially decrease them and reduce soil water runoff and erosion. For the environmental advantages this practice can bring, policymakers are recommended to afford funding opportunities for farmers to implement AWD and reduce water consumption and also to provide them support and capacity-building for helping them to implement AWD correctly and minimize yield reductions if it is considered an appropriate technology for the specific land (Anschell & Salamanca, 2021).

1.2.6 Nitrogen Use Efficiency

Plant uptake of inorganic soil nitrogen (N) may be enhanced through the implementation of several practices and technologies. Nitrogen use efficiency (NUE) is calculated as the ratio between the amount of N fertilizer utilized by the crop and the amount of applied N fertilizer. NUE represents the N balance, value used as agro-environmental indicator to assess the efficiency of agricultural production to convert the applied N fertilizer into harvested product (Brentrup & Palliere, 2010). While N balance may be expressed as kg N per country or per hectare and provides a quantification of the amount of nitrogen that is not captured by the produce and that will be probably lost (by nitrate leaching), NUE is a percentage and is related to the utilization of N fertilizer.

N is a critical and essential nutrient required for the growth and development of all plants and is the main agricultural fertilizer. From the literature, it results that crops utilize only half of the total N fertilizer applied, and the remaining half follows different pathways increasing pollution of the surrounding environment. For the farmers, this means a diminished gain with respect to the cost paid for the fertilizer and an increase in pollution, with further negative consequences for the farmers themselves. Thus, NUE enhancement is a key issue in crop improvement programs and agronomic management systems. The low N use by plants is due to several causes, including N volatilization, surface runoff, leaching, and denitrification. Researchers aim to improve NUE by means of agronomic management practices in conjunction with high-throughput technologies, to achieve a reduction of the currently intensive N application on agricultural lands and to limit its impact on the environment. Agronomic, biotechnological, and genetic tools and strategies need to be integrated to improve N assimilation efficiency by agricultural crops and modify agricultural systems to make them responsive to global needs, protecting the environment and its resources (Govindasamy et al., 2023).

1.2.7 Introduction of Renewable Energy in Agriculture

Numerous strategies exist to enhance the introduction/use of renewable energy in agriculture, for example, pyrolysis plants, solar panels, windmills, and water pumps. The promotion of renewable sources in agriculture aims to strengthen the use of solar energy for the production of electricity and biogas. Particular attention needs to be paid to relaunching private investments, as well as attracting foreign investments. In the frame of smart agriculture, the connection between the agricultural-energy-water sectors through the integration of traditional practices with the use of renewable energy and sustainable water management must be reinforced.

Agrivoltaic farming represents another interesting technology. The simultaneous use of arable land for both power generation by solar photovoltaic and agriculture allows to increase energy production and efficiency, yielding at the same time

several agricultural and environmental benefits. Several studies have shown that agrivoltaic farming may have a positive influence on agricultural produce, increasing land-use efficiency, allowing limited water loss, and attaining high power from solar radiation. It has been proved that solar panels positioned above plants can generate up to 10% more electricity (https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/agrivoltaics-alone-could-surpass-eu-photovoltaic-2030-goals-2023-10-12_en, last accessed on July 15, 2024).

1.3 Conclusion and Future Perspectives

Climate-smart agriculture (CSA) approach also presents important limitations. In relation to the affordability of its technologies and the limited financial services, farmers with higher socioeconomic status may afford more efficiently the cost of agrochemicals (fertilizers) and labor, which are crucial for enhancing crop yield and realizing sustainable farming practices. According to the World Bank as well as to FAO, in order to implement CSA programs for small-scale farmers, it is necessary to integrate research results, development, and training, in a comprehensive approach, including the selection of adapted and diverse varieties and genetic lines that are at the basis of the agricultural resilience (Mizik, 2021; Mpala & Simatele, 2023). In addition, the promotion of organic farming practices is in line with the principles of sustainability and environmental management, since the use of synthetic chemicals is minimized, preferring natural methods to reinforce plant response to biotic threats, at the same time ameliorating soil health and fertility.

Finally, CSA benefits are evident for the environment and for human health, and the large-scale implementation of its related practices and technologies would point towards a sustainable future of agriculture. Anyway, there are several limitations that need to be overcome, particularly concerning the economic cost of running this effective transition in worldwide agriculture. The development and implementation of best practices and technologies should be tailored to specific farming systems and supported by scientific evidence.

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Chapter 2

AI-Powered Strategies: Fortifying Crops Against Climate Stress



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2.1 Background

It is crucial to advocate for laws and regulatory frameworks that provide support. Governments and policymakers have a crucial role in encouraging sustainable agriculture practices and the uptake of climate-resilient technologies. It is crucial to invest in capacity-building and education initiatives to provide significant long-term changes in climate variables, including rainfall, temperature, wind, and snow patterns are referred to as climate change (Pope et al., 2022). It is projected to profoundly impact agriculture by directly and indirectly affecting crops, soils, livestock, and pests (Hatfield et al., 2020). Soil processes, most particularly soil fertility, could be highly affected by climate change, a slow-moving phenomenon that results in minor temperature and precipitation variations over a long duration. The most recognized consequences on climate change occur via elevated levels of CO₂ and increasing temperatures but also by changes in salinity (Zandalinas et al., 2022). But crop production is particularly vulnerable to climate variability, as contradictory signals from higher temperatures and increased CO₂ levels will affect yields of various plants—not all negatively. Because of greenhouse gas emissions, the average global temperature has increased by 0.9 °C during the nineteenth century (Zhao et al., 2017). According to projections, this warming trend will surpass 1.5 °C by 2050 (Calicioglu et al., 2019) which has profound implications for agriculture. Climate change intensifies temperature extremes, water-related stresses, soil

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degradation, and pest and disease pressures, collectively posing significant challenges to sustainable food production (Roudier et al., 2011). While the exact impacts on global crop yields remain uncertain, changes in temperature, CO₂ levels, and rainfall patterns are expected to negatively affect agricultural productivity (Roudier et al., 2011).

Simultaneously, global food demand is expected to surge significantly in the coming decades due to population growth. The Food and Agriculture Organization (FAO) estimates that food demand may rise by 50–54% by 2050. This escalating demand, exacerbated by human activities accelerating climate change, underscores the urgent need for resilient agricultural practices. Addressing these challenges requires proactive measures to safeguard food security amidst changing climatic conditions.

2.2 Influence of Climate Stress on Soil Fertility and Crop Fertility

Shifts in precipitation and temperature are anticipated to profoundly impact land suitability and crop growth patterns worldwide. One major consequence of these changes will be the expansion of arable land at higher latitudes due to milder winters, while semi-arid and arid regions may become less suitable for crop production. For instance, in East Africa, rising temperatures are rendering highland areas less suitable for traditional wheat cultivation, although these regions may become more favorable for other grain crops (Aryal et al., 2020). Without adapting crop varieties to these changing conditions, global warming is projected to reduce wheat and maize yields by 5.2–12.2% in rain-fed areas and by 5–14% in irrigated regions by 2050 (Tesfaye et al., 2017).

Additionally, the rate of land degradation is increasing at an alarming rate due to climate change, resulting in nutrient-deficient soils and increased desertification. It has been determined that this expanding menace is a serious worldwide issue. Research from the Global Assessment of Land Degradation and Improvement (GLADA) indicates that around 25% of Earth's land area is now classified as degraded. Due in large part to human activity and climate change, it is predicted that there would be an annual loss of 15 billion tons of productive soil and the impact on the lives of 1.5 billion people would be the consequence of this deterioration. Drought and desertification have forced the abandonment of 500 million hectares of farmland, according to a 2017 UN Environment Programme research, leading to major environmental and social issues (Arora, 2019).

Extreme droughts, which are becoming increasingly frequent due to climate change, significantly impact crop productivity by causing nutrient immobilization and salt accumulation in soils. These conditions lead to soil degradation, making it dry, unhealthy, and eventually infertile. Consequently, farmers often abandon these degraded lands, creating both economic and social problems. Additionally, climate

change is causing a marked increase in the frequency and severity of floods. The European Academies' Science Advisory Council (EASAC) has reported that extreme weather phenomena, such as floods, have increased by 50% in the last 10 years and are now occurring at a rate that is four times higher than it was 20 years ago. For instance, the severe floods in Kerala, India, in 2018 resulted in the loss of topsoil and essential nutrients, leading to diminished agricultural productivity that may persist for years unless effective and timely measures are taken.

Moreover, rising sea levels and heavy rainfall can decrease the availability of agricultural land in coastal regions, leading to soil salinity. This leads to crop stress that disrupts crucial physiological processes like respiration, photosynthesis, and transpiration, thereby jeopardizing food availability and security in these regions. Climate change also threatens the genetic diversity of crops; as climatic conditions evolve, farmers may stop cultivating certain varieties, potentially leading to their extinction. Despite improvements in crop management and varying input use, both wheat and rice face significant challenges from terminal heat stress, with wheat being particularly vulnerable (Arshad et al., 2017). Recent statistics suggest that there has been a deceleration in the worldwide growth of wheat yields in recent decades, as shown by studies conducted by Wiesmeier et al. (2015) and Cassman and Grassini (2020). The South Asian region, which heavily relies on wheat and rice as essential food sources, is expected to see significant decreases in crop yields due to increasing temperatures and limited water availability. Climate change has caused a 5.2% decrease in wheat yields in India over the last 30 years (Gupta et al., 2017). Continued global warming might lead to a potential decline of up to 50% in wheat yields by 2050. The most significant declines are anticipated in Bangladesh (60%), India (40%), and Pakistan (27%) (Bandara & Cai, 2014; Aryal et al., 2020). According to Knox et al. (2012), it is expected that rice production will decline by 40% in India, 32% in Nepal, and 10% in Bangladesh. Global climate change is expected to negatively affect several crops such as maize, coarse grains, sunflower, millet, soybean, cotton, and sugarcane.

2.3 Role of AI to Mitigate Climate Change in Agriculture

Amid the complex challenges presented by climate change, artificial intelligence (AI) offers a promising approach to addressing the intricacies and uncertainties in agriculture. AI encompasses technologies such as deep learning and machine learning, which are capable of generating predictive models that can be used to analyze and interpret intricate patterns in large datasets.

The integration of AI technologies in agriculture represents a transformative evolution that spans precision farming, livestock management, and supply chain optimization. By leveraging AI-driven insights, agriculture can transition towards a more sustainable model capable of resiliently responding to climate-related disruptions (Jain et al., 2023).

AI applications in agriculture are diverse and impactful, encompassing the use of data-driven approaches for crop management and livestock care. Through the analysis of data collected from sensors, drones, and satellite imagery, AI facilitates the creation of detailed field maps that highlight areas requiring specific interventions such as water, fertilizer, or pest control (Singh & Kaur, 2022). The systematic integration of AI into agricultural practices involves data collection from various sources, followed by rigorous analysis using AI algorithms to uncover patterns and trends (Kar et al., 2022). This analytical capability empowers farmers to make informed decisions regarding resource allocation, disease prevention, and operational efficiencies. For instance, AI recommendations on irrigation and fertilization contribute to resource conservation while minimizing environmental impact. Furthermore, AI-driven automation in agriculture, such as robotic planting and harvesting, streamlines labor-intensive tasks, thereby increasing operational efficiency and allowing farmers to focus on strategic management and market engagement. This comprehensive use of AI technologies not only enhances productivity but also strengthens the agricultural sector's resilience to climate stressors, ensuring food security amidst evolving environmental challenges.

2.4 The Integration of Remote Sensing, Simulation Models, and Artificial Intelligence(AI)

Remote sensing satellites and drones collect extensive data on soil moisture, temperature, vegetation health, also other variables. AI systems then analyze this data to forecast crop yields, identify early signs of stress, and optimize resource management. This integration improves the capacity to monitor and adapt to climate variability and supports the development of sustainable farming practices. Such advancements help ensure long-term food security and agricultural sustainability amid changing environmental conditions. Unmanned aerial systems (UAS), commonly known as drones, are a crucial component of remote sensing technology in agriculture. Remote sensing involves collecting data about crops and soil from a distance using sensors on satellites or aerial platforms like drones. Drones and other unmanned aerial systems (UAS) are useful for this because they can survey large areas at low altitudes with great detail, offering detailed insights into crop health, growth, and yield. This data complements satellite remote sensing by providing finer spatial resolution, enabling precise monitoring and management of agricultural fields (Fig. 2.1). By combining UAS with crop simulation models and machine learning, the quality and usefulness of remote sensing data are improved, allowing for better decisions in precision agriculture (Jung et al., 2021).

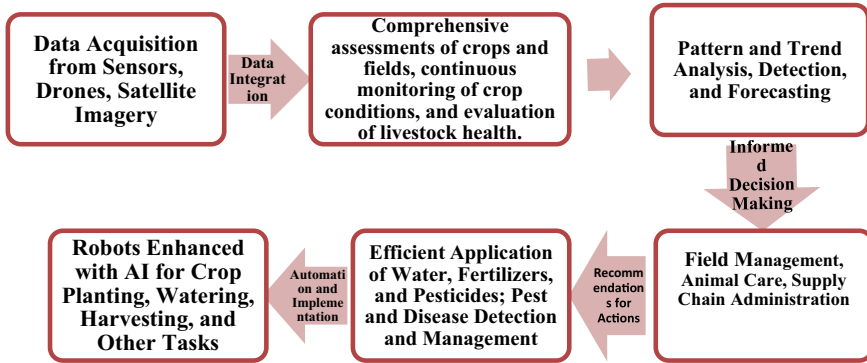


Fig. 2.1 Flow chart of implementing AI and remote sensing in agricultural management from data collection to automation

2.5 Application of Remote Sensing

Remote sensing is widely used in climate-resilient agriculture for several purposes, such as:

2.5.1 Vegetation Monitoring

Remote sensing systems provide multispectral and hyperspectral images of agricultural landscapes, allowing for the examination of several vegetation indices like the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). These indices are essential for assessing crop health, biomass production, and photosynthetic activity. By leveraging these metrics, farmers can effectively monitor crop growth and identify stress factors such as water scarcity, nutrient deficiencies, and pest infestations, thereby enhancing their capacity to manage and optimize crop production (Alazzai et al., 2024).

2.5.2 Land Use Mapping

Remote sensing data aids in mapping land cover and land use patterns, which helps in identifying changes in agricultural practices, deforestation, urbanization, and natural habitats. These maps are crucial for informing land management decisions, conservation strategies, and policy interventions aimed at fostering sustainable land use and ecosystem preservation.

2.5.3 Soil Moisture Monitoring

Techniques such as radar and thermal imaging in remote sensing are employed to measure soil moisture content and surface temperature, providing crucial information on soil water availability, evapotranspiration rates, and drought conditions. This data is vital for effective irrigation management, crop planning, and water resource allocation, thereby enhancing agricultural resilience against climate variability and water scarcity.

2.5.4 Crop Yield Estimation

Remote sensing-based models and algorithms integrate satellite imagery, weather data, and crop growth parameters to estimate crop yields and production potential. These models allow farmers, policymakers, and agribusinesses to predict harvests, grasp market dynamics, and formulate well-informed decisions regarding market strategies, planting schedules, and crop selection.

2.5.5 Climate Monitoring and Risk Assessment

Remote sensing data provides valuable information on climate variables such as temperature, precipitation, and humidity, which are critical for understanding and mitigating climate risks. This data supports the development of climate models and forecasts, enabling farmers to anticipate and prepare for extreme weather events like floods, droughts, and heatwaves, thereby reducing potential crop losses.

2.5.6 Disease and Pest Management

High-resolution remote sensing imagery is effective in identifying early signs of diseases and pest infestations in crops. By analyzing changes in vegetation indices and spectral signatures, these technologies can locate affected areas and monitor diseases and pests incidence. This information enables focused treatment applications, minimizing crop damage and reducing the use of chemical inputs.

The convergence of artificial intelligence (AI) with remote sensing methodologies in climate-resilient agriculture encompasses a variety of sophisticated techniques:

Data collection: Obtaining high-quality, high-resolution data from a varied range of sources—such as satellite imagery, unmanned aerial vehicles (UAVs), ground-based sensors, and weather stations—is crucial for good development of AI

models, fine-tuning predictive algorithms, and validating outcomes. This process includes essential data preprocessing activities like image correction, geometric rectification, and spectral normalization, which ensure uniformity and precision in data interpretation.

Algorithm development: Developing AI algorithms and machine learning models requires the meticulous selection of relevant features, training datasets, and optimization strategies. In remote sensing, widely used supervised learning methods including support vector machines (SVM), random forests, and deep learning neural networks are employed for tasks such as classification, regression, and clustering.

Model validation: The validation of AI models and remote sensing outputs involves rigorous comparison with actual ground observations, field data, and benchmark datasets. Cross-validation methods like k-fold validation, leave-one-out validation, and bootstrapping are applied to evaluate the model's performance and its ability to generalize across different spatial and temporal contexts.

Spatial analysis: Spatial analysis techniques, including spatial autocorrelation, spatial interpolation, and spatial clustering, are employed to examine and depict patterns, trends, and relationships within remote sensing data. Geographic information systems (GIS) and geostatistical approaches are essential for integrating spatial data, performing geospatial analysis, and offering decision support for agricultural management and planning.

Temporal analysis: Analyzing remote sensing time series data facilitates the monitoring of seasonal changes in vegetation, phenological shifts, and other land surface processes over time. Time series analysis methods, such as trend analysis, seasonal decomposition, and anomaly detection, are used to uncover long-term trends, seasonal variations, and irregularities in the data, which are instrumental in formulating climate adaptation strategies and managing risks effectively.

2.6 Machine Learning

In agriculture, machine learning is implemented to analyze data regarding soil, weather, and plant health, thereby facilitating the formulation of well-informed decisions regarding irrigation, fertilization, and insect control procedures. It also plays a critical role in the development of predictive models that are designed to reduce waste and optimize crop yields. One of the most noteworthy advantages of machine learning is its capacity to enhance over time. The algorithm's accuracy and efficacy are enhanced as it processes more data and refines its parameters. Nevertheless, machine learning is not without its obstacles. Effective training necessitates a substantial amount of high-quality data and can be computationally intensive, necessitating a significant amount of memory and processing capacity. Machine learning has the potential to transform a variety of industries, despite the obstacles it faces. Machine learning applications that are more sophisticated and

efficient are anticipated to emerge in a variety of disciplines as a result of ongoing technological advancements.

2.7 Internet of Things (IoT)

The internet has become indispensable across various sectors, including agriculture. In this field, an effective method involves monitoring agricultural fields through IoT technology. This approach utilizes sensors to analyze a wide range of agricultural parameters, facilitated by wireless sensor networks. IoT refers to the interconnection of devices such as sensors via the internet, enabling seamless data transfer. It forms a vast network where numerous objects are connected to a global information infrastructure. Agricultural IoT sensors are vital for precision agriculture, as they collect detailed information about crop and soil conditions, weather patterns, and water usage. This data helps farmers optimize resource management and make informed decisions, leading to improved crop yields and more effective farming practices. These sensors are fundamental in converting physical signals into digital data within Ag-IoT systems, making the selection of the right sensors crucial for optimal performance. Innovations in sensor technology have significantly broadened the application of IoT throughout all phases of agriculture, from planting to the final packaging of products. Key stages in agriculture—including planting, soil and nutrient management, water management, pest and disease control, yield monitoring, and post-harvest processing—benefit from the incorporation of advanced sensing technologies (Kakarla et al., 2022).

Soil-degradable sensors are a new development in the field of agricultural technology. They are intended to monitor critical soil parameters, including moisture levels, temperature, acidity, pH, and nutrient content. These sensors possess the unique characteristic of naturally degrading within the soil over time, which provides numerous advantages. They eliminate the necessity for retrieval, mitigate the risk of soil contamination, and offer valuable insights into soil dynamics without disrupting the ecosystem (Sui et al., 2021). Furthermore, the use of biodegradable soil moisture sensors that are both low-maintenance and cost-effective can enhance our comprehension of the variability in soil water availability across various locations and times within a field (Table 2.1).

Continuing from the discussion on sensors, we can delve into the practical applications and the future prospects of IoT and WSN technologies in various domains, particularly in agriculture the incorporation of IoT and WSN technologies into agriculture showcases the profound impact of these advancements. Precision agriculture (PA), enhanced by IoT and WSN, focuses on detailed observation and management of crops to optimize yield and resource use. These tools enable farmers to make educated choices based on real-time data on soil conditions, crop health, weather patterns, and irrigation needs.

Furthermore, Internet of Things technologies can automate a variety of agricultural chores. For example, automated irrigation systems that utilize real-time data

Table 2.1 Types of sensors and their measurements (Chamara, 2021)

Groups of physical variables	Sensor-driven measurement	Sensors for quantifying parameters	Literature-based applications for monitoring soil, crops, and microclimates
Sonic	Wave strength, phase, polarization, spectrum, and wave speed	Sound sensor, ultrasonic distance sensor	Identification of hardwood borer (Potamitis et al., 2019), estimation of crop canopy height (Yuan et al., 2018), and measurement of wind velocity (Kameoka et al., 2017)
Biological	Biomass, species type, number, density, and chlorophyll level	RGB camera, multispectral sensors, load cell	The wet weight of plants and estimated above-ground biomass (Chamara, 2021) can be measured Continuous measurement of plant weight is also conducted (Chen et al., 2016)
Chemical	Air quality, gas type, electrical conductivity, pH	Volatile organic compounds	Air quality (Bagley et al., 2020), soil pH, irrigation water pH, soil conductivity, irrigation water conductivity, soil gas flux, factory house CO ₂ , and O ₂ demand attention (Chen et al., 2019a)
Electrical	Charge, current, potential difference, electric field, resistance, conductivity, permittivity, amplitude, phase, polarization, spectrum, electric field	Soil moisture sensor; capacitive or resistive humidity sensor	Soil moisture (Chamara, 2021), air humidity (Bagley et al., 2020), estimation of soil nutrients, measurement of stomatal conductance, sap flow monitoring, estimation of evapotranspiration, and measurement of soil electrical conductivity (Chen et al., 2019a)
Magnetic	Magnetic field, magnetic flux, permeability, (amplitude, phase, polarization, spectrum)	Wind speed parameter	Measuring wind direction and speed (indirect method) (Chen et al., 2019a)

from soil moisture sensors may modify water distribution based on current soil conditions, weather predictions, and crop needs. This automation lowers labor costs and eliminates the danger of human mistakes, resulting in more efficient and sustainable agricultural operations (Rao et al., 2022).

Wireless sensor networks (WSNs) are crucial for environmental monitoring, with applications spanning wildlife conservation, pollution tracking, and disaster management, in addition to agriculture. In the agricultural context, WSNs can track microclimates across various sections of a field, offering detailed insights into how local environmental differences impact crop growth. This fine-grained monitoring facilitates the development of targeted strategies to enhance crop resilience and productivity (Koshariya et al., 2023).

The future of IoT and WSN in agriculture looks bright, with emerging advancements in AI and machine learning set to significantly enhance their functionality. AI algorithms can process the extensive data collected by IoT devices, identifying

patterns and forecasting trends that may not be immediately obvious to human analysts. For instance, AI can anticipate pest invasions or disease outbreaks, enabling farmers to implement preventative measures to safeguard their crops.

Additionally, the advancement of biodegradable sensors offers a sustainable approach to managing electronic waste. These sensors naturally break down after their functional use, reducing environmental impact. They are capable of monitoring soil conditions such as moisture, temperature, and nutrient levels, delivering crucial data while being environmentally friendly. The integration of IoT, WSN, and AI is transforming agriculture through precise, data-driven management practices. As technology advances, its applications in agriculture and other fields are expected to grow, providing innovative solutions to critical issues such as food security, environmental sustainability, and resource management.

2.8 Integration of Artificial Intelligence in Genome Editing

One remarkable biotechnological advance that has recently surfaced is genome editing, with artificial intelligence (AI) significantly enhancing its precision and efficiency. AI algorithms are essential for analyzing large genomic datasets, predicting off-target effects, and refining editing techniques, thereby accelerating the development of tailored genetic modifications. For instance, AI-driven tools like CRISPR-Cas9 have been used to engineer specific gene edits in crops, resulting in traits such as improved disease resistance and higher yields (Smith et al., 2020). Furthermore, machine learning algorithms facilitate the understanding of complex genetic interactions, predict phenotypic outcomes, and guide the selection of optimal editing targets (Angermueller et al., 2016). This integration of genome editing and AI represents a promising synergy with significant potential to advance agricultural biotechnology and crop improvement strategies.

Genome editing has revolutionized crop development by allowing breeders to precisely insert or remove DNA regions inside the genome. There has been extensive usage of transcription activator-like effector nucleases (TALENs) and zinc finger nucleases (ZFNs) for over 20 years. However, the CRISPR/Cas9 system, which originated in *Streptococcus pyogenes*, has emerged as the most flexible tool accessible to breeders (Zhang et al., 2017). This approach promotes the introduction of advantageous features and speeds up the creation of climate-resilient crop varieties.

In the past decade, advancements in sequencing technologies have greatly influenced crop genotyping practices. The advent of new fast, high-throughput genotyping procedures for whole crop populations has made molecular tools available for widespread application in plant breeding (Armin et al., 2017). Over a dozen reduced representation sequencing (RRS) techniques and four whole-genome resequencing (WGR) styles are included in this group. Genome assembly and improvement, relation mapping, marker supported and genomic selection, genome-wide association studies (GWAS), and the most popular genotyping methods are all examined in this study, along with their suitability for crops with varying genome sizes and

complexity (Elshire et al., 2011). WGR proves particularly profitable for genotyping biparental cross populations with small- to moderate-sized genomes, delivering the most cost-effective approach per marker data point. RRS styles, while varying in how well they work for different tasks, generally have analogous costs per marker data point and are generally more budget-friendly for new systems or for genotyping populations with large genomes or high inheritable diversity (Poland et al., 2012). Indeed, though RRS is still an affordable option, WGR is anticipated to become more common as the cost of sequencing keeps dropping.

CRISPR/Cas9, a rapidly progressing genome editing technology, has been effectively applied to various organisms, including model and crop plants. Cas9 is an RNA-guided DNA endonuclease that can be targeted to specific genomic sequences using a custom-designed guide RNA, making CRISPR/Cas9 an affordable and user-friendly technology. In certain plant species, it can produce homozygous knockout mutants in just one generation (Zhang et al., 2017). Alongside other sequence-specific nucleases, CRISPR/Cas9 is set to revolutionize fundamental research and plant breeding. Its simplicity and reliability make it a highly attractive tool for plant biology, particularly for generating gene knockouts. Additionally, CRISPR/Cas9 can knock out entire gene families and create large chromosomal deletions by incorporating multiple sgRNAs into a single delivery vector. Despite the difficulties in leveraging homologous recombination for gene addition and dealing with off-target mutations in plants, CRISPR/Cas9 stands at the forefront of genome editing technologies. With a broadened toolkit and bioinformatics support, it promises significant advancements in both fundamental and applied plant research (Gao et al., 2022).

By using CRISPR RNAs (crRNAs), the CRISPR/Cas system provides bacteria and archaea with a defense mechanism against viruses and plasmids. The system is guided to quiet the invading DNA by these crRNAs. Occasionally, a two-RNA structure is formed when the mature crRNA joins forces with a trans-activating crRNA (tracrRNA). This structure instructs the Cas9 enzyme to initiate the creation of double-stranded breaks in the target DNA. The complementary strand is cut by the Cas9 HNH domain, while the noncomplementary strand is cut by the Cas9 RuvC-like domain. The promise of RNA-guided genome editing is shown when these RNAs are fused to form a chimera, which directs Cas9 to make targeted DNA cuts (Jinek et al., 2012).

Genome editing has revolutionized crop improvement by allowing precise changes to DNA sequences. A custom guide RNA (gRNA) and the Cas9 enzyme are typically introduced into plant cells, where Cas9 induces a double-strand break (DSB) three base pairs upstream of the NGG motif, also known as the protospacer adjacent motif (PAM). The cell repairs this break using nonhomologous end joining (NHEJ), a process that often results in frameshift mutations and gene knockouts (Shan et al., 2013). Alternatively, precise genetic insertions can be achieved through homologous recombination (HR) using a donor DNA template. The CRISPR/Cas9 system has been successfully employed to disrupt genes associated with disease resistance in crops. For example, editing the OsERF922 gene in rice enhances resistance to blast disease, while modifying the TaMLO gene in wheat increases resistance to powdery mildew (Chen et al., 2019b). In rice, targeting the OsERF922 gene

with CRISPR/Cas9 led to mutant plants with various insertions or deletions (InDels) at the target site, which increased resistance to blast disease while preserving other agronomic traits. In wheat, both TALEN and CRISPR-Cas9 technologies have successfully introduced targeted mutations in the TaMLO genes, resulting in durable and broad-spectrum resistance to powdery mildew (Luo et al., 2023).

Genome editing is also being used to address abiotic stresses in staple crops. For example, in maize, a stronger promoter was used to replace the ARGOS8 gene's promoter, enhancing drought tolerance. Transgenic maize plants with increased ARGOS8 expression showed improved grain yields under drought conditions while maintaining regular yields with optimal watering. This highlights CRISPR-Cas9's potential in developing drought-resistant crops. Rice blast disease is a major threat to rice globally, and host resistance is the most cost-effective method for controlling it. CRISPR/Cas9 has proven especially effective in improving resistance by targeting the OsERF922 gene. Research has shown that CRISPR/Cas9 creates mutant rice plants with improved blast resistance, known as C-ERF922-induced mutants, which display fewer blast lesions and maintain similar agronomic traits to wild-type plants. Additionally, using multi-target sgRNAs to hit multiple sites within the OsERF922 gene has further increased resistance (Wang et al., 2016).

In a comparable manner, CRISPR-Cas9 improved maize drought tolerance by modifying an enzyme called ARGOS8, which is a negative regulator of ethylene responses. The expression of ARGOS8 was enhanced and grain production was improved in drought circumstances by inserting the GOS2 promoter into its 5'-untranslated region. As a whole, sequence-specific nucleases like CRISPR/Cas9 have become an effective tool for producing more robust agricultural types, increasing yields, and making crops more resistant to pathogens and abiotic stressors (Shi et al., 2017). Because they enable plants to finish important development stages before encountering environmental stressors, early-maturing cultivars may provide substantial benefits in an era when climate change is affecting agriculture. For instance, early-maturing tomato cultivars have been developed by deleting the flower-repressing gene SP5G. Rice cultivars that are more resistant to the effects of climate change include those that have secondary qualities, such as root and leaf characteristics, and primary traits, such as tolerance to heat, cold, and drought, introduced during the seedling and reproductive stages. To improve resilience to abiotic stressors, CRISPR techniques are essential for studying and altering genes from wild rice cousins (*O. officinalis*, *O. nivara*, and *O. glaberrima*) (Zeng et al., 2020).

Plants typically flower in response to changes in day length, which can limit where they can be grown. To expand their cultivation areas, it is important to adjust how plants respond to day length. For instance, in tomatoes, researchers have eliminated the influence of day duration by specifically targeting the florigen paralog and flowering repressor SELF-PRUNING 5G (SP5G). By using CRISPR/Cas9 to create mutations in SP5G, they have sped up flowering and promoted a more compact, determinate growth habit in field tomatoes, leading to earlier harvests. This gene editing technique has allowed tomatoes to be grown outside their original equatorial region in South America, showcasing how gene editing can quickly improve crop yields.

Rice, a crucial staple for half the world's population, is key to meeting growing calorie needs. As the global population increases, maintaining food security will heavily rely on rice. However, with the reduction in rice-growing areas, it is essential to minimize yield losses from abiotic and biotic stresses. Climate change has a negative impact on both the quality and quantity of rice production. A possible approach to creating climate-smart rice varieties that will support and increase production in shifting conditions is CRISPR/Cas technology. By harnessing beneficial phenotypes and genetic factors, genome engineering can enhance tolerance to major abiotic stresses related to climate change. Leveraging insights from wild rice relatives can facilitate the introduction of advantageous alleles into cultivated rice, and CRISPR/Cas-mediated strategies can produce resilient phenotypes to address climate challenges. Overcoming issues such as off-target effects and undesirable phenotypes is critical for effective implementation (Zafar et al., 2020).

Selecting drought-tolerant cereal varieties has increasingly centered on assessing grain yield under stress, with grain filling closely linked to the functionality of the flag leaf. To ensure effective grain filling during drought, the flag leaf must either maintain its function or be effectively reprogrammed. However, our understanding of flag leaf performance and adaptations under stress is still limited. Research on the function and adaptation of rice flag leaves under drought is particularly sparse, and similar gaps exist for other cereals. The current body of research on flag leaf function across different cereals is fragmented, with few studies delving into the molecular and mechanistic details of adaptations to drought. Gaining a deeper understanding of these characteristics at the molecular level could help identify reliable markers for robust flag leaves, enabling more efficient screening of diverse germplasm and supporting the development of innovative drought-tolerant breeding materials (Liang et al., 2017).

Genome editing holds great promise for speeding up the domestication of new crops from wild relatives or lesser-known plants with traits that help them thrive in extreme climates. This technology allows for precise changes to important genes involved in domestication, quickly expanding the genetic diversity of these crops to make them more adaptable to climate change. Using multiplex CRISPR systems to target multiple genes at once can make these genetic modifications faster and more efficient. However, challenges such as off-target effects, low efficiency of homologous recombination (HR), restrictive protospacer adjacent motif (PAM) sequences, and regulatory hurdles have led to the development of advanced techniques like DNA-free genome editing, base editing, and prime editing. These newer methods aim to overcome the limitations of traditional genome editing, offering more precise and effective options for improving crops (Lin et al., 2020).

A simplified form of the *Streptococcus pyogenes* type II CRISPR/Cas system, which uses Cas9 and a single guide RNA (sgRNA), has emerged as a potent tool for targeted gene deletion in several species, including yeast, human cells, zebrafish, fruit flies, bacteria, and yeast. *Arabidopsis* and tobacco are dicot plants that have adapted this system for their usage, whereas rice and sorghum are monocot crops. *Agrobacterium tumefaciens* was used to introduce the system to *Arabidopsis* and tobacco (Shan et al., 2013). The system consisted of genes expressing Cas9, sgRNA,

and a mutant green fluorescent protein (GFP) that did not function. An error-prone method of DNA repair was used by the Cas9/sgRNA complex to cleave the mutant GFP gene at certain places, resulting in GFP genes that could function. DNA sequencing verified the Cas9/sgRNA system's effectiveness in targeted mutagenesis. The promoter regions of the bacterial blight susceptibility genes OsSWEET14 and OsSWEET11 were targeted by Cas9/sgRNA constructs in rice protoplast cells. DNA sequencing confirmed the presence of mutations at the target locations. The Cas9/sgRNA method has shown promise for plant genetic engineering, with promising results in both model plants and crop species. This bodes well for future advancements in agriculture and scientific study (Jiang et al., 2013).

Traditional genome editing methods that use recombinant DNA (rDNA) can lead to random integration into the host genome, which may cause unintended genetic changes or DNA damage (Sander et al., 2014). These methods also face regulatory hurdles due to the introduction of foreign DNA, which can label the organisms as genetically modified. DNA-free genome editing (DFGE) addresses these issues by minimizing off-target effects and avoiding foreign DNA. DFGE has been effectively applied to rice and tobacco using CRISPR-Cas9 ribonucleoprotein (RNP) complexes delivered to protoplasts. A particle bombardment-based DFGE approach has also been developed for editing wheat and maize (Zhang et al., 2016).

A variety of cell types, including human cell lines, animals, and plants, are now capable of precise genome editing by using RNA-guided engineered nucleases (RGENs) generated from the CRISPR/Cas system. Problems like off-target effects and unintended DNA integration from plasmid vectors might arise with these approaches (Cong et al., 2013). To address these concerns, cultured human cells, including fibroblasts and pluripotent stem cells, which are notoriously difficult to transfect, are directly exposed to pure recombinant Cas9 protein together with guide RNA. In order to reduce off-target effects while performing efficient site-specific alterations, this approach employs RGEN ribonucleoprotein (RNP) complexes (Kim et al., 2014).

The RNPs interact with chromosomal DNA almost immediately and are quickly degraded, lowering the risk of off-target mutations and causing less stress to cells, resulting in more successful colonies compared to plasmid-based techniques.

Genome editing offers substantial opportunities for advancing functional genomics and drug discovery. Sequence-specific nucleases allow for precise targeting and disruption of nearly any protein-coding gene in the human genome, creating a valuable library of cell culture knockouts. This is crucial for understanding gene functions, identifying drug targets, and developing therapeutic nucleases. For instance, a zinc-finger nuclease (ZFN) targeting a gene related to an HIV-1 receptor in human stem cells is currently undergoing clinical trials as a potential AIDS treatment (Perez et al., 2008).

Genome editing offers significant potential for advancing crop improvement. Advances in crop DNA sequencing and bioinformatics have illuminated the genetic factors affecting key agronomic traits, including disease and drought resistance, allergenicity, and nutritional quality. Researchers have made impressive strides by designing sequence-specific nucleases to target and knock out specific genes, as exemplified by the development of mildew-resistant bread wheat. The first

commercial crop produced through genome editing—a herbicide-tolerant canola variety from Cibus Global—was approved for use in Canada in 2014, with its market introduction anticipated in 2016 (Waltz, 2014).

One way to address regulatory concerns about GMOs is to edit plant genomes without adding foreign DNA. Tobacco, *Arabidopsis thaliana*, lettuce, and rice protoplasts may be transfected with preassembled complexes of pure Cas9 protein and guide RNA, among other plant species. With this approach, targeted mutagenesis may be achieved at rates as high as 46% (Woo et al., 2015). The end product of these genetic manipulations are tiny, naturally occurring variations in DNA that are both germline-transmissible and altered in a way that is difficult to detect.

Genome editing is made much more precise and efficient with targeted DNA double-strand breaks. CRISPR-Cas9's ease of use and adaptability have made it the technique of choice. Using DNA vectors to deliver double-strand break reagents was the traditional method for modifying plant genomes. Generative mutagenesis in maize embryo cells has been achieved using biolistic delivery of pre-assembled Cas9-gRNA ribonucleoprotein (RNP) complexes; no DNA or selectable markers were used in this process. This method allows for the rapid breeding of several crop species by restoring plants with high-frequency mutant alleles (Svitashev et al., 2016).

2.8.1 Base Editing

Base editing controlled by CRISPR-Cas9 provides an accurate way to change a single DNA base to another without using a repair template. This is shown by the fact that cytidine deaminases change cytosine (C) to uracil (U), which is subsequently interpreted as thymine (T), leading to a change from C•G to T•A. Wheat, maize, and tomatoes are just a few crops that have benefited from this method, which has made it easier to analyze gene functions and create stress-adapted cultivars. Understanding gene and protein functions in the genomics age requires reverse-genetic techniques. While traditional methods such as insertional mutagenesis and transgenic approaches have limitations, chemical mutagens can induce single-nucleotide changes across plants (Gaudelli et al., 2017). Recent improvements in detecting these changes have enhanced the efficiency of this process. Base substitutions introduce various allelic variations, providing deeper insights into protein function. Subsequently, the necessity of genome-wide screening for point mutations and natural variations is becoming more critical for the advancement of plant functional genomics. A potent method for producing agricultural plants with desired features, TILLING (Targeting Induced Local Lesions IN Genomes) is particularly useful for species that lack modern genetic tools. It removes the barriers that have previously prevented genetic research from using agricultural plants as model organisms. Modern reverse-genetic techniques like TILLING offer new opportunities to advance genetic studies across diverse species (Chen et al., 2019b). Mutations in gene structure may occur at random due to the use of double-stranded DNA breaks in conventional genome editing techniques. In contrast, base editing offers a more exact way by directly replacing one DNA base with another,

eliminating the necessity for donor templates and the risk of double-stranded breakage. This method involves using a cytidine deaminase enzyme in conjunction with CRISPR/Cas9 to make C → T (or G → A) substitutions by converting cytidines to uridines. This method improves the accuracy and breadth of genome editing by successfully repairing point mutations in murine and human cell lines with little indel creation (Komor et al., 2016). Researching gene functions and improving agricultural features have both benefited from the extensive use of the CRISPR system in plants. Potentially new avenues for plant genome engineering have opened up thanks to developments in precise base-editing technologies and DNA-free delivery systems, which should help mitigate regulatory concerns and minimize off-target consequences. These base-editing systems are effective for creating point mutations and introducing valuable agronomic traits, promising a bright future for plant genome editing.

2.8.2 Prime Editing

Prime editing, introduced by Anzalone et al., 2019 and further adapted for plants by Lin et al., 2020 marks a significant advancement in genome editing technology. It allows for precise base-to-base conversions, insertions, and deletions using prime editing guide RNA (pegRNA) (Marzec & Hensel, 2020). This method utilizes a modified Cas9 endonuclease fused with a reverse transcriptase, enabling targeted edits without double-strand breaks or the need for donor DNA templates. Prime editing has shown high efficiency with minimal by-products and reduced off-target effects in both human and plant cells. In crops like rice and wheat, optimized prime editors have facilitated precise mutations, improved functional genomics, and aided in the development of climate-adaptive traits (Anzalone et al., 2019). Although there are regulatory concerns, prime editing presents considerable potential for creating climate-smart crops when combined with traditional breeding techniques.

2.9 Enhancing Genetic Improvements with Phenomics and Artificial Intelligence (AI)

Advances in phenomics and genomics have significantly increased the data available to breeders, aiding in the improvement of crop yields. Although genomic selection (GS) has made notable progress in cereals and legumes, accurately predicting complex traits such as yield remains difficult due to the complex interactions between genetic and environmental factors. These traits are often governed by numerous minor genes with cumulative effects, which can be missed in smaller populations (Hickey et al., 2017). Additionally, the nonlinear nature of the genotype-phenotype relationship poses challenges for many statistical models.

Even with decreasing costs for genome sequencing and the introduction of new genetic assays using high-throughput sensors and imaging technologies, accurately predicting and selecting traits for specific environments still relies on sophisticated modeling. To handle these intricacies, breeding programs are increasingly relying on omics technologies including microbiomics, phenomics, epigenomics, proteomics, metabolomics, and genomics in conjunction with climate and field data (Batley & Edwards 2016). An effective strategy for creating climate-resilient, high-yielding, stress-tolerant crops may be achieved by integrating phenomics, genomics, and AI.

The world's agricultural sector is poised for a second green revolution as we confront the triple threat of a rapidly expanding human population, harsh weather events, and finite resources. With the correct integrated software, we can now directly select yield and resilience-related characteristics from huge germplasm collections, thanks to advances in phenomics, genomics, and environmental control (Li et al., 2018).

Traits identified during development and across different environments can be assessed using genome-wide association studies (GWAS) and functional structural plant models (FSPMs). These tools help predict growth and reproduction, simulating regional variety trials to enhance productivity under difficult conditions. Despite the gap between projected food needs and current production levels, new breeding technologies and strategies, including genomic selection (GS), are crucial for bridging this divide (Wang et al., 2018). GS has already shown its value in animal breeding and is increasingly important in plant breeding. By combining GS with advanced technologies and crop growth models, we can significantly improve crop genetics. A key element of using high-throughput genomics and phenomics is connecting genotype to phenotype. Next-generation AI plays a vital role in integrating extensive multi-omics data, allowing for more accurate predictions and improvements. This approach is essential for developing high-yield, climate-adaptable crops, which is critical for ensuring food security and supporting sustainable ecosystems (Crossa et al., 2017).

2.9.1 Field Phenomics

Advances in high-throughput phenotyping (HTP) are crucial for accelerating plant breeding efforts focused on climate resilience. Innovations like advanced sensors, unmanned aerial vehicles (UAVs), and high-resolution imagery have significantly enhanced phenotypic data collection. HTP enables the efficient evaluation of plant architectural characteristics and the early identification of promising genotypes by offering automated and accurate measurements of agronomic and physiological parameters. Methods like RGB imaging, 3D scanning, thermal and hyperspectral sensing, and fluorescence imaging have proven effective for detecting and tracking plant diseases (Li et al., 2022). Given the challenges posed by global population growth, shifting demographics, and environmental variability to food security, integrating advancements in plant phenotyping with genetic tools is essential for

improving and sustaining crop yields with limited resources. Robotic imaging systems and analysis tools based on computer vision are examples of recent innovations. Spectral Vegetation Indices (SVI) derived from UAV imagery, such as NDVI, SR, and GNDVI, have shown particular promise in phenotyping, especially in Mediterranean climates. The effectiveness of GNDVI in forecasting grain production has been well-established, making it a critical tool for addressing the issues presented by population expansion and climate change. Improving crop root architecture is essential for better moisture and nutrient use efficiency, profiling the root phenome remains complex. Recent developments in imaging and sensor technologies, along with automated image analysis methods like deep learning, are transforming root phenotyping and aiding crop selection for global food security. Recent progress in high-resolution field-based high-throughput phenotyping (HTP) is driven by advancements in sensor technology and advanced computing. These developments allow for precise screening of field-grown crops, offering valuable insights into the genetics of quantitative characteristics like yield and disease resilience. Effective phenotyping platforms depend on several key components: advanced imaging technology and sensors, high-quality data products for machine learning, robust data management systems, and automated environmental data collection. These technologies are crucial for developing improved crop varieties giving higher yield and improved disease tolerance (Crain et al., 2018).

New methods for plant genetics and genomic characterization, rendered achievable by integrating rapid-extensive phenotyping with genome-wide association studies (GWAS), are greatly improving crop breeding. This is especially true considering the current phenomenon of climate change in our world. Plant picture analysis and environmental stress phenotyping are two examples of the big and complicated phenomics datasets that are finding more and more applications for deep learning (DL) (Singh et al., 2018).

Despite rapid advancements in high-throughput sequencing, traditional plant phenotyping methods have not kept pace. In order to narrow the difference, the establishment of high-throughput rice phenotyping facilities (HRPF) has enabled the monitoring of 13 traditional agronomic characteristics and two new traits in the growth phase of rice. GWAS of these traits identified 141 associated loci, highlighting key genes such as the Green Revolution semi-dwarf gene, *SD1*. This demonstrates that high-throughput phenotyping can effectively replace traditional methods, offering valuable insights into gene identification and enhancing our comprehension of the genetic structure of vital characteristics (Yang et al., 2014). Deep learning, a branch of machine learning, excels at integrating and analyzing extensive and diverse datasets to make precise predictions about complex phenomena. Its growing use in plant science is revolutionizing the analysis of extensive datasets from high-throughput phenotyping and genotyping. Recent studies have demonstrated the effectiveness of deep learning in assessing plant stress through digital imaging, improving decision-making accuracy, data management, and versatility across different situations. The ongoing application of deep learning tools promises significant advancements in plant science and crop enhancement.

2.9.2 Next-Generation-Based Genomic Selection

Breeding for climate resilience is increasingly relying on genomic selection (GS), especially for complex traits involving multiple genes. GS employs predictive models to evaluate the combined impact of numerous genetic markers on desirable traits. Enhancing prediction accuracy with GS can shorten breeding cycles and improve crop yields. Omics data—encompassing gene expression, metabolite levels, and epistatic interactions—often provides more precise phenotype predictions than single nucleotide polymorphisms (SNPs) alone, due to their closer association with the phenotype. Despite this, integrating these omics layers into statistical models is still a work in progress, which can affect their overall effectiveness. Common methods like mixed-effect linear and Bayesian models are used to pinpoint key predictive SNPs. Integrating comprehensive omics and environmental data is crucial for advancing breeding efforts and refining trait selection. Emerging AI technologies offer significant potential for genomic selection by streamlining the integration and analysis of large datasets across genomics, phenomics, and other molecular layers (such as transcriptomics, proteomics, and epigenomics). This advanced fusion can reveal complex biological interactions, enhancing breeding strategies to address climate challenges and other objectives. AI-based solutions are increasingly utilized in cloud data centers, which provide significant GPU resources to support various AI applications. As high-bandwidth network connectivity expands, cloud-based infrastructure for AI becomes more accessible, enabling farmers and breeders to seamlessly upload data from multiple platforms (Montesinos-López et al., 2018).

It is still unfeasible to rely exclusively on machine learning (ML) and deep learning (DL) to speed up breeding efforts, despite the fact that these technologies have shown great promise in phenomics and genomics. Translational processes are a challenge to the plant research community because apart from phenomics, proteomics, metabolomics, transcriptomics, and genomics, each of these fields provides only a limited amount of information. Effectively integrating these diverse data layers remains a major challenge for advancing plant breeding and research. Integrating multiomics data is crucial for advancing plant breeding. Although progress is being made within the plant research community, success hinges on scalable solutions and widespread adoption. Effective collaboration among research infrastructures is essential, alongside efforts in capacity building and technology transfer. A coordinated effort will be needed to develop frameworks to support and finance AI innovations in plant breeding. It is imperative that the public and private sectors increase their investment, particularly through partnerships and venture capital. The emphasis will move from technical performance to developing new farming models that are advantageous to both people and the environment as next-gen AI becomes more widely used (Zingaretti et al., 2020).

2.9.3 Speed Breeding: Accelerating Crop Improvement

The techniques used to boost the yields of staple crops like maize, rice, and wheat are not able to meet future demand, particularly as the effects of climate change intensify. These crops' lengthy generation periods—which normally only permit one to two generations annually—present a significant obstacle. A solution is provided by speed breeding, which allows for up to six generations annually by prolonging the growing seasons with more daylight and regulated temperatures. Chickpeas, rice, canola, barley, spring wheat, and chickpeas have all demonstrated success with this technique.

With the global population rising, along with increased consumption of meat and dairy products and a greater reliance on biofuels, the demands on agriculture are growing. Crops including maize, rice, wheat, and soybean are stagnating or even declining in some areas, while other regions have managed to increase yields. Increasing investment in underperforming regions and implementing ways to raise returns in high-performing regions are necessary in order to tackle these difficulties (Watson et al., 2018).

With up to six generations annually for crops like spring wheat and barley and up to four for canola, speed breeding has shown to be efficient in considerably reducing generation times, as opposed to the usual two to three generations attained under conventional settings. Through the use of regulated lighting, this technique accelerates the generation cycle by means of single seed descent (SSD). It may be combined with state-of-the-art breeding methods including high-throughput genotyping, genome editing, and genomic selection to further enhance crops (Hickey et al., 2019).

Innovative strategies are being developed to meet the growing agricultural demands. For example, integrating speed breeding with an adopted backcross method has led to establish barley lines with multiple disease resistances within 2 years, highlighting the advantages of combining speed breeding with phenotypic screening. For rice, which needs to increase production to meet future needs, rapid generation advance (RGA) is recommended as a standard breeding method. The International Rice Research Institute (IRRI) has demonstrated that RGA can significantly improve yield and cost-effectiveness compared to traditional methods. Furthermore, combining speed breeding with modern breeding technologies and adequate investment provides a powerful approach to boosting crop yields and improving resilience to climate change. This integrated strategy is crucial for meeting the growing demand for food and tackling the difficulties of global food security (Hickey et al., 2019).

Allelic variety found in landraces and crop wild relatives (CWR) must be swiftly identified and used in order to produce crop varieties that are climate change-adaptable. This is where speed breeding comes in. Finding novel sources of resistance to leaf rust in the collection of Vavilov wheat is one noteworthy example of how speed breeding and gene-specific molecular markers may be used to effective effect. Moreover, integrating speed breeding with advanced gene editing techniques can further enhance crops' capacity to withstand biotic as well as abiotic stressors

induced by climate change. Single guide RNA (sgRNA) is used in traditional CRISPR gene editing to guide Cas9 enzymes to particular DNA sequences. This process can be improved by creating “CRISPR-ready” genotypes containing heterologous Cas9 genes. For instance, transformants with a Cas9 transgene can be used as donors in marker-assisted backcrossing to produce elite inbred lines. Innovative systems like Express Edit address the challenges of traditional in vitro plant material manipulation by accelerating gene editing. These systems avoid the use of tissue culture and foreign DNA, facilitating precise allelic modifications while sidestepping genetically modified organism (GMO) regulations. Without requiring tissue culture, methods like CRISPR-Cas9 ribonucleoprotein (RNP) complexes have been effectively used to make single or multiplex changes in crops like maize and wheat. The prompt creation of new crop types is important in order to address the problem of feeding the world’s projected 10 billion inhabitants. The use of cutting-edge technologies like de novo domestication, genome editing, high-throughput phenotyping, marker-assisted selection, genotyping, and genomic selection may be sped up by speed breeding. This approach enables plant breeders to keep pace with environmental changes and increasing food demands (Ghosh et al., 2018).

Puccinia triticina is responsible for leaf rust (LR), a serious disease that affects wheat crops all over the world. Using wheat cultivars with genetic resistance—including both adult plant resistance (APR) and all-stage resistance—is crucial for managing LR in a sustainable manner. APR is particularly advantageous because it tends to be more durable, helping to lower the pathogen’s ability to evolve, and is typically governed by multiple genes. New sources of APR were sought out in a recent study that used a varied collection of wheat lines from the N. I. Vavilov Institute of Plant Genetic Resources. Out of 300 lines screened, 83 had known APR genes such as Lr34, Lr46, and Lr67. Additionally, phenotypic screening under controlled conditions revealed 50 lines showing APR, with these results aligning with field data. Subsequent field evaluations identified 13 lines demonstrating consistently high APR levels, presenting valuable options for future breeding programs. Integrating rapid generation advances with phenotyping in controlled environments is proving to be an effective strategy for speeding up the incorporation of new resistance genes into adapted wheat varieties. This approach leverages modern technologies and streamlined breeding practices to accelerate the development of improved wheat cultivars (Singh et al., 2011).

In several species, including plants, the CRISPR/Cas9 system has shown to be a useful tool for targeted genome editing. A unique multiplex CRISPR/Cas9 system allows six sgRNA modules to be co-expressed in a single binary vector in *Arabidopsis*. This strategy produces homozygous sextuple mutants by targeting six of the 14 PYL families of ABA receptor genes in a single transformation. This skill is crucial for carrying out in-depth functional assessments of gene families and pathways, which broadens our comprehension of intricate genetic relationships. The goal of optimizing the CRISPR/Cas9 system is to improve crop breeding accuracy by tackling problems like off-target mutations and transgene integration. One of the latest developments is the use of CRISPR/Cas9 ribonucleoprotein (RNP) complexes to modify the genome of bread wheat. Compared to conventional CRISPR/Cas9 DNA editing methods, this strategy produces transgene-free mutants

and has a lower chance of off-target consequences (Liang et al., 2018). The technique's encouraging results point to a great chance of creating commercially viable genome-edited agricultural plants. In order to increase resistance to climate change, speed breeding expedites the exploitation of allelic variation in landraces and crop wild relatives. This method transforms attempts to enhance crops by enabling precise genetic alterations without introducing foreign DNA when paired with CRISPR gene editing. Recent implementations of this integrated method, for instance, have enabled the discovery of novel sources of wheat leaf rust resistance. Furthermore, speed breeding combined with cutting-edge genotyping methods like rAmpSeq speeds up the stacking of advantageous haplotypes. This makes it possible to create new cultivars that perform better in a variety of ways, such as higher resistance to pests and increased tolerance to unfavorable environmental circumstances. The use of allelic variety from crop wild relatives and landraces is greatly accelerated by speed breeding, which is essential for improving climate resistance. It enables precise genetic alterations without introducing foreign DNA when paired with CRISPR gene editing, which significantly advances crop development. Recent research using this integrated method has revealed novel wheat leaf rot resistance sources. Additionally, researchers may quickly build advantageous haplotypes by combining modern genotyping methods like rAmpSeq with speed breeding. This makes it possible to create new cultivars with superior characteristics, such as stronger pest resistance and greater capacity to adapt to hard climates.

2.10 Conclusion

The confluence of climate change and agriculture epitomizes a critical global challenge, with profound implications for food security and environmental sustainability. The adverse effects of rising temperatures, erratic precipitation patterns, and the increasing frequency of extreme climatic events are already manifesting in declining soil fertility, reduced crop yields, and the expansion of degraded lands. These changes necessitate urgent interventions to safeguard the future of global food production. The deployment of advanced technologies, notably discussed here, artificial intelligence (AI) and genome editing, emerges as a pivotal strategy to counteract these challenges. AI-driven innovations facilitate precision agriculture, enabling the optimized use of resources and enhancing the resilience of crops to environmental stressors. Simultaneously, genome editing technologies, such as CRISPR/Cas9, hold the potential to develop climate-resilient crop varieties, thereby ensuring sustained agricultural productivity under shifting climatic conditions. Looking ahead, the integration of AI and genome editing into mainstream agricultural practices represents a promising avenue for future research and development. Future research works should be focused on refining these technologies to enhance their accessibility and effectiveness in diverse agricultural settings, particularly in regions most vulnerable to climate change. Moreover, interdisciplinary approaches that combine advances in biotechnology, data science, and environmental sciences will be crucial

in addressing the multifaceted nature of climate impacts on agriculture. By fostering innovation and collaboration across these fields, we can develop resilient agricultural systems capable of withstanding the challenges posed by a rapidly changing climate.

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Chapter 3

Breeding Approaches for Intervention in Biotic and Abiotic Stress Elevation in Agriculture



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3.1 Background

Climate change is a thoughtful concern to the world's food security because it affects crop productivity in many regions, including Europe, Asia, and sub-Saharan Africa. For example, the EU's 2018 heatwave and drought decreased cereal production by 8%, resulting in a shortage of fodder and higher commodity prices. Developing nations, especially those in tropical latitudes, are more vulnerable because of their inadequate infrastructure and resilience (Hristov et al., 2023). Over two billion people are classified as food insecure, and approximately 10% of the world's population suffers from hunger. These issues are made worse by the COVID-19 pandemic. Considering the predicted population (9.7 billion) by 2050, crop productivity needs to rise by about 70% while reducing the negative effects on the environment (Wudil et al., 2022).

The never-ending battle against biotic and abiotic stressors in agriculture is a significant barrier to global food security (Fig. 3.1). The difficulties that biotic and abiotic stresses present to crops are made worse by climate change, which

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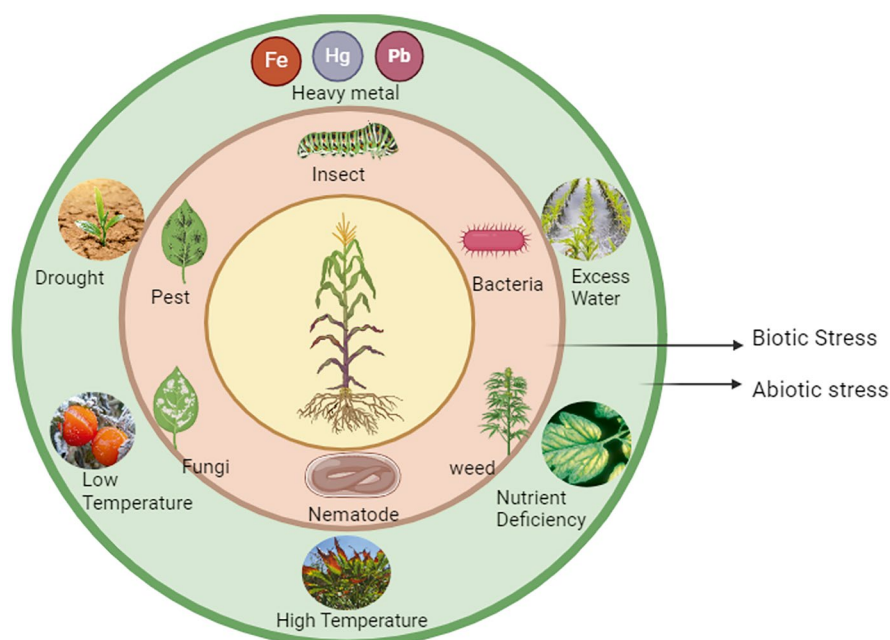


Fig. 3.1 Diagrammatic representation of different biotic and abiotic stresses for crops

emphasizes the need for innovative strategies to increase plant resilience. Developing environmentally sound and sustainable adaptation strategies is imperative to increase crop productivity in the face of these daunting obstacles (Ahmad et al., 2021). Adopting breeding techniques to create crop varieties with increased resistance to these stressors is a promising avenue for intervention. The current chapter examines the applicability and efficacy of biotechnological approaches, molecular breeding methods, and conventional breeding methods in the management of biotic and abiotic stresses in crops. Further, holistic breeding methods that take into account the interactions between various stressors are crucial for sustainable agriculture.

Furthermore, the socioeconomic and ethical aspects of stress tolerance breeding are also covered in this chapter, in addition to the technical aspects. It talks about how stress intervention techniques affect farming communities, taking into account things like technology access, intellectual property rights, and the importance of farmer participation. By comprehending the obstacles and prospects in this domain, we can endeavor to create robust crop varieties that can withstand the harsh effects of a shifting climate and guarantee sustenance for upcoming generations.

3.2 Effect of Various Types of Stresses on Plants

Stress generally refers to any deviation from a feature or phenomenon's normal state. Stress in agriculture shows up as an adverse impact on crop growth, development, productivity, and quality. The plants' responses to stress include changes in gene expression, adjustments to cell metabolic activities, and adjustments to physiological and biochemical processes. Stress in the environment is divided into two categories: biotic stress, which originates from interactions between living things, and abiotic stress, which is the product of interactions between living things and inanimate environmental elements. Environmental factors that surpass plants' tolerance threshold give rise to abiotic stresses and include drought, soil salinity, temperature change, flooding, and soil acidity. These stressors interfere with vital physiological functions in plants, which reduces water and nutrient absorption, impedes photosynthesis, and eventually lowers yield (Ahluwalia et al., 2021). The organisms that impose adverse impacts on crop growth and yield consist of parasitic plants, nematodes, fungi, bacteria, viruses, and insects. By feeding on plant tissues, spreading illnesses, or vying for resources, these organisms can directly harm plants, lowering crop quality and yield. Stresses have a profound effect on plants,

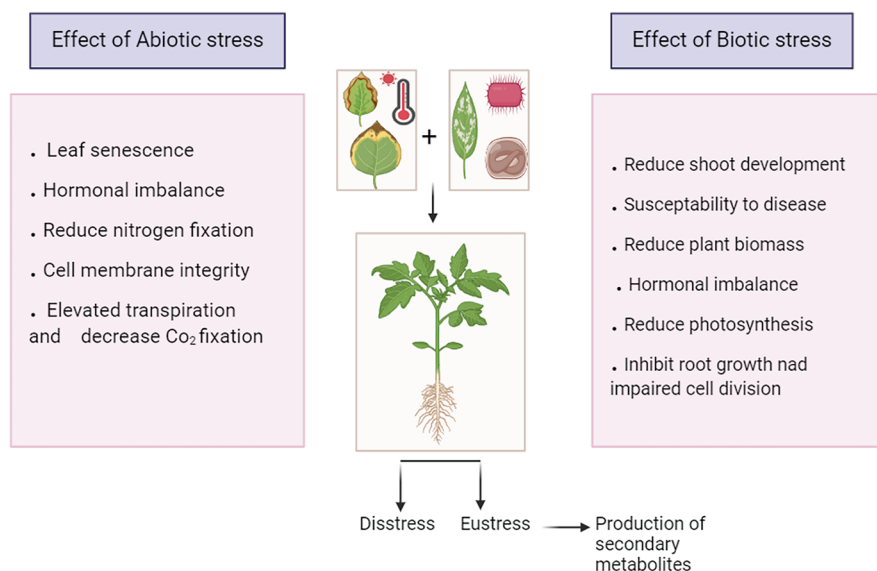


Fig. 3.2 Graphical representation of plant response to stress [When a plant encounters a stressful situation (the stressor), it processes the information and mounts a physiological defense (stress response). When a stimulus is low or persistent, plants can reversibly modify their metabolism to produce secondary metabolites or increase resistance—a process known as eustress. However, when a stimulus is high or persistent, the plant's adaptive capacity may be exceeded, leading to permanent damage or death—a process known as distress. Weeds, microorganisms, insects, and parasites are examples of biotic stress. Cold, light, drought, salts, heavy metals, heat, and UV radiation are examples of abiotic stress]

affecting their fundamental processes of growth and development (Fig. 3.2), including the absorption of water, photosynthesis, nutrients, cell division, hormone regulation, and biomass accumulation in general.

3.2.1 Drought and Flooding Stress

Reduced water availability leads to lowering of turgor pressure, wilting, and reduced leaf area due to reduced cell expansion, stomatal closure to minimize water loss through transpiration, and altered hormonal signaling, specifically an increase in abscisic acid (ABA) levels (Wu et al., 2022). Thus, reduced carbon dioxide intake hinders photosynthesis, plant growth slows down, and nutrient uptake becomes less effective, all of which contribute to decreased biomass production and yield. Flooding stress causes hypoxia, nutrient imbalances, and root rot by limiting the amount of oxygen available to the roots. To withstand water stress, plants have developed adaptations such as drought tolerance, osmotic adjustment, and efficient water use.

3.2.2 Salinity Stress

Salinity stress changes the soil's osmotic potential, which makes it more difficult for plants to absorb water; this leads to water stress that is similar to drought conditions, resulting in water imbalance, decreased turgor pressure, and inhibited cell elongation. High concentrations of salt also cause ion toxicity, oxidative stress, and metabolic imbalances within plant cells, which are physiological disruptions that impede normal plant growth processes, such as root and shoot development, and nutrient absorption (Mushtaq et al., 2020).

3.2.3 Temperature Stress

Extreme temperatures (cold or heat) can damage plant tissues, alter enzyme activities, disrupt photosynthesis, and reduce growth rates. Cold spells can cause frost damage, which can cause tissue death and cellular damage while heat stress results in oxidative stress by producing more reactive oxygen species (ROS), denaturing proteins, damaging photosynthetic machinery, and accelerating water loss through transpiration. These negative consequences limit biomass accumulation, impede photosynthesis, lower fruit set and flower formation, and ultimately affect crop productivity.

3.2.4 *Light Stress*

Plants may experience stress due to inadequate or excessive light levels, types, or duration. The production of biomass, carbon assimilation, and photosynthesis are all decreased by shade stress. Excessive levels of light can harm photosynthetic pigments and induce photoinhibition and oxidative stress (Roeber et al., [2021](#)). To cope with light stress, plants control the absorption of light, the movement of chloroplasts, and photoprotective mechanisms.

3.2.5 *Pathogen Stress*

Pathogens such as fungi, bacteria, viruses, and nematodes infect plants, interfere with cellular processes, and frequently cause outward signs such as leaf spots, wilting, necrosis, and stunted growth (Sood et al., [2021](#)). Wheat plants infected with powdery mildew exhibit white powdery growth on leaves, reduced chlorophyll content, and lower grain quality (Matić et al., [2018](#)).

3.2.6 *Herbivory Stress*

Herbivores like insects, mites, and mammals feed on plant tissues, causing physical damage, defoliation, reduced photosynthesis, and yield losses. Maize plants infested with corn borers show tunneling damage in stems, reduced ear development, and decreased yield (Rodríguez et al., [2021](#)).

3.2.7 *Allelopathic Stress*

Certain plants secrete secondary metabolites called allelochemicals, which prevent nearby plants from growing. Allelopathic stress is the result of these substances interfering with the germination, development, or growth of other plant species. This reduces biodiversity in ecosystems and creates competition.

3.2.8 Nutrient Stress

Nutrient imbalances or deficiencies (e.g., nitrogen, phosphorus, potassium) lead to chlorosis, stunted growth, poor root development, and reduced yield. For example, citrus trees with iron deficiency show yellowing leaves with green veins, reduced fruit size, and poor fruit quality.

3.2.9 Air Pollution Stress

Elevated levels of air pollutants like ozone, sulfur dioxide, and nitrogen oxides cause leaf injury, reduced photosynthesis, oxidative stress, and impaired plant growth. For example, soybean, wheat, maize, and rice plants exposed to ozone show stippled or bronzed leaves, reduced leaf area, and decreased crop yield (Sharps et al., 2021). Air pollution stress can be somewhat tolerated by plants with pollution-responsive genes and pollution-tolerance traits.

3.2.10 Soil Compaction Stress

Soil compaction reduces root growth, aeration, water infiltration, and nutrient uptake, leading to poor plant health, shallow root systems, and reduced yield. For example, apple trees in compacted soil exhibit restricted root expansion, increased waterlogging, and decreased fruit production (Choi et al., 2020). Plants have evolved strong stems, extensive root systems, and flexible tissues to withstand mechanical stress.

3.3 Stress Physiology

Understanding plant stress physiology is essential for a breeder to develop strategies for elevation of the biotic and abiotic stresses. To detect stress signals, plants have receptors such as temperature sensors, ion channels, water channels (aquaporins), photoreceptors, and pattern recognition receptors (PRRs). Plant hormones including jasmonic acid, ethylene, cytokinins, salicylic acid, and abscisic acid are produced and released in response to stress signals. By controlling stomatal closure, growth inhibition, metabolic pathways, gene expression, and defense mechanisms, these hormones function as signaling molecules that coordinate stress responses.

In stress responses, nitric oxide, reactive oxygen species, and calcium ions (Ca^{2+}) act as the signaling factors (Ravi et al., 2023). Protein phosphorylation, ion fluxes, antioxidant defense, and programmed cell death (apoptosis) are among the cellular

processes they mediate. Stress-responsive genes (SRG) encode proteins, including enzymes (like catalase and superoxide dismutase), transcription factors, chaperones, heat shock proteins (HSPs), dehydrins, and defense proteins (ul Haq et al., 2019). The expression of SRG is controlled by transcription factors like MYB, WRKY, bZIP, NAC, and DREB/CBF (Bhat et al., 2024). Plants store compatible solutes (osmoprotectants) like proline, sugars, polyols, and amino acids in response to salinity and drought to preserve turgor pressure, water uptake, and cellular osmotic balance. Plants prevent oxidative damage caused by reactive oxygen species under stress conditions by producing enzymatic (glutathione reductase, catalase, peroxidases, and superoxide dismutase) and nonenzymatic (ascorbate, glutathione, and tocopherols) antioxidants (Mansoor et al., 2022).

Plant stress memory and gene expression are controlled by epigenetic mechanisms such as DNA methylation, histone modifications, chromatin remodeling, and small RNA-mediated gene silencing (Ashapkin et al., 2020). In plant populations, epigenetic modifications can confer stress memory, heritable traits, and transgenerational stress resilience. Plants are primed for enhanced defense responses against pathogens and pests through the mechanisms of induced systemic resistance (ISR) and systemic acquired resistance (SAR), which offer long-lasting protection beyond the initial stress exposure (Kamle et al., 2020). Natural selection, genetic recombination, mutation, and gene flow all contribute to the evolution of adaptive traits, genetic diversity, and population dynamics in plants. Genetic diversity and phenotypic features that confer resilience to particular stressors in their native habitats are exhibited by stress-adapted populations and ecotypes. Gene editing, genomic selection, marker-assisted selection, and other breeding techniques are used in plant breeding programs to create crop varieties that are more resilient to biotic and abiotic stresses and have higher yields and quality (Nerkar & Devarumath, 2022). The complex range of molecular, cellular, physiological, and ecological processes that underpin plants' capacity to perceive, react, adapt, and survive in harsh environmental circumstances is known as stress physiology. The interplay of genetic factors, hormonal signaling, metabolic pathways, structural adaptations, epigenetic regulation, phenotypic plasticity, and evolutionary dynamics shapes plant stress responses and their fitness and performance in demanding environments. Stress physiology research is ongoing and contributes to global efforts to address climate change, food security, and environmental sustainability. It also improves our understanding of plant stress resilience.

3.4 Genetic and Molecular Breeding Approaches for Crop Improvement against Various Abiotic and Biotic Stresses

A crucial component of agricultural research and crop improvement is stress tolerance breeding, especially in light of climate change and environmental challenges. Stressors that affect crop productivity globally include salinity, drought, high

Table 3.1 Integrated genetic and breeding approaches for crop improvement against biotic-abiotic stresses

Breeding approach	Response to stress in different crops	References
Transgenic approaches and marker-assisted selection	Insect and nematode resistance; drought, salinity, heat stress, and herbicide tolerance in horticultural crops	Parmar et al. (2017)
miRNAs in plant growth development and stress resistance	Arabidopsis, soybean, maize, and rice for hormonal signaling, salt tolerance, flowering regulation, and stunt and stripe virus resistance, respectively	Anwar and Kim (2020)
Genomics-assisted breeding and omics-assisted breeding to develop stress-resilient and high-yielding crops	Marker-assisted backcrossing, marker-assisted recurrent selection, marker-assisted selection, advanced backcross QTL, allele addition or deletion through genome editing, genomics selection, and haplotype-based breeding for disease resistance, abiotic stress resistance, plant growth, and quality traits in food crops	Tyagi et al. (2024)
Genomics and marker-assisted improvement of vegetable crops	Tomato, pepper, eggplant, lettuce, spinach, cucumber, and chicory: Disease and insect resistance, abiotic stress tolerance, and fruit quality improvement	Simko et al. (2021)
Marker-assisted selection and introgression of salt tolerance genes	Saltol QTL introgression into high-yielding indica rice by marker-assisted backcrossing	Marè et al. (2023)
Transgenic approach, marker-assisted selection, and host plant resistance	RNA interference, genome editing by CRISPR/Cas9, genetic transformation, and marker-assisted selection for the development of insect-resistant crops	Kumari et al. (2022)
RNAi and CRISPR/Cas technologies	Resistance of crops to pathogenic bacteria, plant parasitic nematodes, and other biotic stress	Yu et al. (2022)
Genomic selection in cereals, pulses, oilseeds, and horticultural crops	Genomic selection was reported to be superior to marker-assisted selection for developing quantitative traits including tolerance to biotic-abiotic stresses, and quality improvement	Budhlakoti et al. (2022)

temperatures, and a variety of biotic stresses. Breeders use a variety of strategies to create cultivars that can withstand stress to overcome these difficulties (Table 3.1). Traditional breeding methodologies serve as the cornerstone for identifying and incorporating stress-tolerant traits from both cultivated varieties and wild relatives of vegetable crops. Genetic diversity within these germplasms harbors genes conferring traits such as drought tolerance, disease resistance, and nutrient efficiency (Singh et al., 2022). Concurrently, molecular breeding approaches, including marker-assisted selection (MAS), genomic selection (GS), transgenesis, genome editing, and RNA interference, offer precise tools to manipulate the genetic makeup of crops (Simko et al., 2021). Through synergistic integration of genetic and molecular approaches, breeders can address the multifaceted challenges faced by vegetable crops, including climate variability, soil degradation, and emerging pest and disease pressures (Fig. 3.3). Here, we provide a concise overview of the comprehensive discussion on the synergistic application of genetic and molecular breeding in crop improvement, underscoring its crucial role in advancing the sustainability of agriculture and global food security.

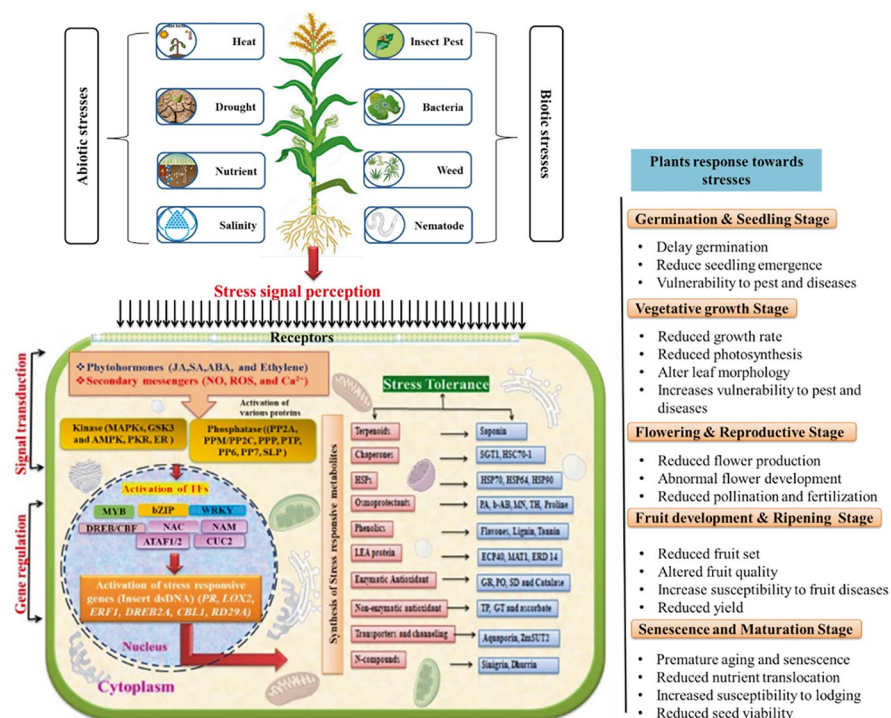


Fig. 3.3 Schematic representation of stress signaling and plant response [*Jasmonic acid (JA)*, *ethylene*, *salicylic acid (SA)*, *abscisic acid (ABA)*, *nitric oxide (NO)*, *reactive oxygen species (ROS)*, *calcium ions (Ca²⁺)*, *glutathione reductase (GR)*, *catalase*, *peroxidases (PO)*, and *superoxide dismutase (SD)*, *ascorbate*, *glutathione (GT)*, and *tocopherols (TP)*, *Polyamines (PA)*, *b-alanine betaine (b-AB)*, *mannitol (MN)*, *trehalose (TH)*]

3.4.1 Conventional Breeding

Traditional techniques are used in conventional plant breeding to create or improve cultivars while maintaining the genetic range of the species. This method seeks to modify plant genomes to accomplish particular breeding goals, and it is inspired by Gregor Mendel's seminal work in genetics. The degree of complexity of the traits being targeted dictates the level of complexity of the breeding process; accordingly, qualitative traits are simpler to control than quantitative traits (Kang et al., 2020). Breeding objectives are established, genetic variability is created or assembled, selection is made, possible candidates are assessed, and new cultivars are released. This is the typical protocol for the breeding process. To guarantee the sustainability of genetic purity and productivity, breeders adjust their techniques to the reproductive traits of the species, whether they are clonally propagated, cross-pollinated, or self-pollinating (Begna, 2021).

Pure lines, open-pollinated lines, hybrids, clonal populations, apomictic, and multilines are the main categories of cultivars, each of which is appropriate for a particular breeding objective and species trait. Reproductive habits of the species dictate the use of different breeding techniques, such as mass selection, pedigree breeding, backcrossing, and family selection. Consequently, conventional plant breeding encompasses a wide range of methods designed to utilize spontaneous genetic variation to create cultivars that possess desired characteristics, guaranteeing crops' continuous enhancement and flexibility.

3.4.1.1 Phenotypic Selection

Plants are visually assessed for stress tolerance traits under stress conditions as part of the phenotypic selection process. Plants with desirable characteristics, like deeper root systems, increased tolerance to particular stresses, or better water use efficiency, are chosen as parents for the following breeding cycle.

3.4.1.2 Crossbreeding

Crossbreeding involves a combination of two or more different parental lines to produce offspring that are more resilient to stress. This method makes use of genetic diversity to introduce new gene combinations that confer traits related to stress tolerance.

3.4.1.3 Selection for Stress-Adaptive Traits

To help plants adapt to stressful environments, breeders look for characteristics like early maturity, smaller leaves that absorb less water, or particular biochemical pathways.

3.4.1.4 Reciprocal Recurrent Selection

This method entails crossing two parental lines, stress-testing the offspring, choosing the top performers, and then crossing those individuals with the other parental line. The goal of this process is to accumulate advantageous alleles from both parents by repeating them over several cycles.

Table 3.2 Introgression breeding for crop improvement against abiotic and biotic stresses

Crop	Hybrids	Hybridization Technique	Stress Addressed	References
Maize (<i>Zea mays</i>)	TZEI 357 × TZEI 411 and TZEI 380 × TZEI 410	Crossbreeding of drought-tolerant parental lines	Drought stress	Adewale et al. (2018)
Wheat (<i>Triticum aestivum</i>)	Cham5*2/ <i>T. dicoccoides</i> and Cham5*3/ <i>T. aegilopoides</i>	Interspecific hybridization with heat-tolerant wild relatives	Heat and drought stress	Aberkane et al. (2021)
Rice (<i>Oryza sativa</i>)	Pokkali, Holdegotal-2, Vojon, Blockkhira, Rajashail, and Hatibejor	Inter-varietal hybridization to combine salt tolerance traits	Salinity stress	Sogir et al. (2023)
Potato (<i>Solanum tuberosum</i>)	Somatic hybrid P8, wild species <i>S. pinnatisectum</i> , progeny MSH/14–112 (P8 × cv. Kufri Jyoti), and <i>S. tuberosum</i> dihaploid C-13	Hybridization with wild potato relatives carrying blight resistance genes	Disease resistance	Tiwari et al. (2021)
Barley (<i>Hordeum vulgare</i>)	8294-01, 235243-01, 224751-01, 238367-01, 230205-01, and 230207-01	Hybridization with drought-tolerant landraces	Drought stress	Shibeshi et al. (2018)
Citrus (<i>Citrus</i> spp.)	‘Valencia’ sweet orange + ‘Femminello’ lemon	Crossbreeding with disease-resistant citrus varieties	Disease resistance	Catalano et al. (2021)
Alfalfa (<i>Medicago sativa</i>)	<i>M. arborea</i>	Interspecific hybridization with disease resistance <i>Medicago</i> species	Frost and disease resistance	Irwin and Bingham (2023)

3.4.2 Pre-Breeding and Introgression Breeding

Pre-breeding and introgression breeding have emerged as significant avenues to enhance genetic diversity and stress tolerance in cultivated crops. Pre-breeding focuses on the exploration and initial evaluation of genetic resources, while introgression breeding is a targeted breeding approach aimed at transferring specific traits from wild relatives to cultivated crops to improve their performance and adaptability. Both strategies are pivotal in expanding the genetic diversity and resilience of cultivated crops in the scenario of environmental change and evolving pest and disease pressures (Singh et al., 2022). Since Dr. Edgar Anderson advocated conventional methods like backcrossing for trait integration in 1949, the meticulous transfer of the desirable characters into elite genotypes has turned out to be a core of crop breeding. Enrichment of genetic diversity through the introduction of desirable traits from wild relatives to elite populations through distance hybridization in combination with pre-breeding approach is the most important technique (Table 3.2).

Enhancing stress tolerance in crops has been made possible through the long-standing agricultural practice of hybridization, which involves combining different

plant varieties to produce offspring with desirable traits (Nerkar & Devarumath, 2022). To create hybrids with better drought tolerance, breeders have combined various parental lines in maize hybridization, as one example. By crossing lines with complementary traits, hybrid maize varieties show increased resilience to drought stress, allowing sustained productivity in areas prone to water scarcity (McMillen et al., 2022). Examples of these complementary traits include deep root systems for water uptake and efficient photosynthesis under water-limited conditions. Likewise, rice varieties that are resistant to salinity, submersion, and pest pressures have been created through hybridization (Sangeetha et al., 2020). Hybridization methods are used in rice breeding programs to combine traits from wild rice relatives that are resistant to flooding and cultivated varieties that are resistant to diseases and pests. When rice farmers in areas prone to floods, salinized soils, and pest infestations cultivate their crops, the resultant hybrids prove to be exceptionally versatile and adaptable to various environmental circumstances. In general, hybridization continues to be an effective method to develop tolerance against stresses in various crops, providing chances to capitalize on genetic diversity and create hardy cultivars that can flourish under difficult circumstances.

3.4.3 *Mutagenesis*

A variety of techniques, including radiation and chemical treatments, have been used to induce genetic mutations in crops known as mutagenesis, which has been used to increase various crops' resistance to stress. Researchers created genetic variations in wheat seeds through mutagenic treatments, which led to plants with deeper root systems, better stress response mechanisms, and increased water use efficiency. These wheat varieties that have been mutagenized, using ethyl methane sulfonate (EMS), show heightened resistance to drought, allowing for continued productivity even in water-scarce environments (OlaOlorun et al., 2021).

Crop varieties with increased disease resistance have been developed in large part thanks to mutagenesis. For example, tomato plants with enhanced resistance to bacterial wilt disease have been produced through the use of mutagenesis techniques. Mutant tomato cultivars demonstrate increased resistance to bacterial wilt, lowering yield losses and the requirement for chemical pesticides (Sharma & Bhattarai, 2019). This is achieved by introducing genetic variations that disrupt pathogen susceptibility factors or enhance the expression of defense-related genes. Crop scientists are still investigating new genetic variations through mutagenesis that can confer resilience to different stresses. This work is important for developing crop varieties that are stress-tolerant and necessary for sustainable agriculture in a changing climate.

3.4.4 Phenomics Platforms

Phenomics platforms make it possible to measure plant traits in a variety of environmental conditions in a high-throughput, nondestructive manner. Breeders can more effectively select superior genotypes and identify stress-responsive traits by combining genomic and phenotypic data. To help with the development of drought-resistant varieties, for example, sophisticated phenotyping techniques have been used to screen maize germplasm for traits linked to drought tolerance (Wu et al., 2021). Phenotypic platforms—which include both images and sensor data—offer a novel method of managing sensors in a range of domains, including industrial automation, environmental monitoring, healthcare, and agriculture. These platforms combine the power of sensors and visual data to optimize workflows and make defensible decisions. An outline of phenotypic platforms' operations and importance in sensor control is provided below:

3.4.4.1 Integration of Sensor and Visual Data

Phenotypic platforms combine sensor data—such as pressure, humidity, and temperature—with camera images (Nabwire et al., 2021). The platform obtains a thorough understanding of the environment or object under observation by merging these two forms of data.

3.4.4.2 Enhanced Perception

Machine learning algorithms for object recognition, anomaly detection, and pattern analysis can interpret images' rich visual information. Conversely, sensor data provides accurate quantitative measurements (Nabwire et al., 2021). When combined, they provide a view of the environment or system under observation that is more comprehensive.

3.4.4.3 Real-Time Monitoring and Analysis

A variety of parameters can be monitored and analyzed in real time using phenotypic platforms. This feature is essential in situations where prompt responses are needed, like in industrial settings where equipment performance needs to be continuously monitored or in precision agriculture where crop health needs to be evaluated quickly (ElMasry et al., 2019).

3.4.4.4 Automation and Control

Based on the gathered data, decision-making procedures can be automated by combining phenotypic platforms with actuators and control systems (ElMasry et al., 2019). For instance, in agriculture, the platform can use sensor data and image analysis to identify indications of pest infestation in a crop field, and then use automated sprayers to release pesticides that are specifically targeted at those signs.

3.4.4.5 Adaptive Systems

By continuously analyzing incoming data, phenotypic platforms can adjust to changing conditions. Through the use of historical data, machine learning algorithms can gradually enhance decision-making, strengthening the system's resilience and efficiency.

3.4.4.6 Applications Spanning Multiple Domains

These platforms find use in a variety of domains. They support disease detection, crop monitoring, and yield optimization in agriculture. They support disease diagnosis, treatment optimization, and patient monitoring in the healthcare industry. They make quality control, predictive maintenance, and condition monitoring easier in industrial settings.

3.4.4.7 Flexibility and Scalability

Because phenotypic platforms are flexible, they can be implemented in systems of different sizes, ranging from small-scale businesses to expansive industrial complexes (ElMasry et al., 2019; Nabwire et al., 2021). They are also adaptable to a variety of use cases due to their flexibility and ability to be tailored to meet the needs of individual applications.

3.4.4.8 Data-Driven Insights

Phenotypic platforms produce insightful information that can guide decision-making processes by compiling and evaluating data from various sources (Nabwire et al., 2021). These realizations may result in more efficient use of available resources, higher output, and enhanced system performance.

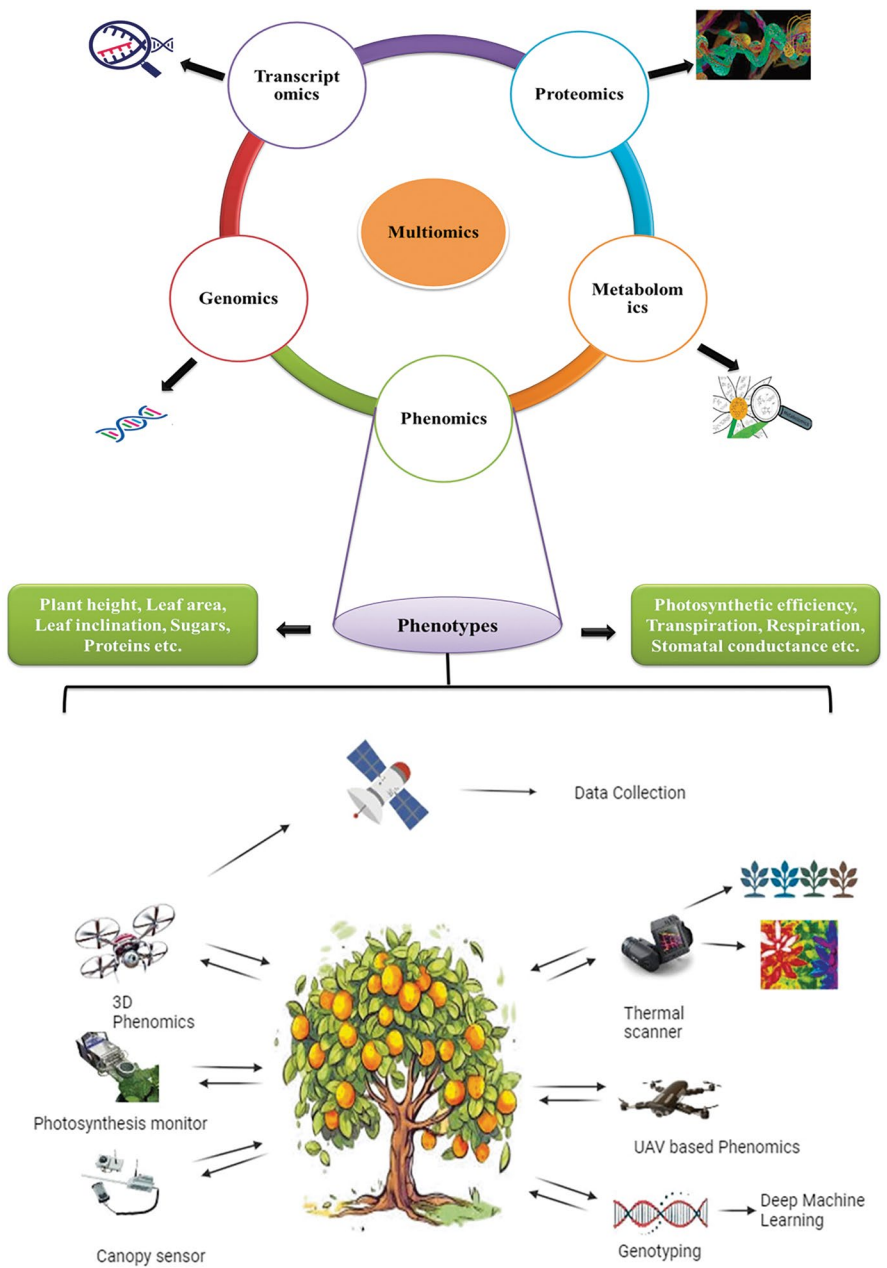


Fig. 3.4 Multi-omics approaches for crop improvement against abiotic and biotic stresses

3.4.5 Genomics Advancements for Abiotic and Biotic Stress Tolerance

In today's omics era, high-throughput sequencing technologies have advanced rapidly, leading to expansion of omics datasets which include genomics, transcriptomics, proteomics, epigenomics, and metabolomics (Fig. 3.4). DNA is a valuable biomolecule that contains an organism's genetic information. By sequencing genomes and understanding their coding and noncoding regions, we can gain insight into many aspects of biology, which holds great promise for improving crops against evolving stresses.

In crop genomics, advancements have primarily been made through marker technologies such as genotyping by sequencing (GBS), next-generation sequencing (NGS) (e.g., Illumina, PacBio, Nanopore), single nucleotide polymorphism (SNP) arrays, and Kompetitive allele-specific PCR (KASP) assays (Gill et al., 2022). Next-generation sequencing (NGS) technologies have further revolutionized sequencing-based genotyping, with methods like Reduced Representation Libraries (RRLs), RAD sequencing, and GBS becoming standard. GBS, in particular, has garnered attention due to its simplified and cost-effective approach, with improvements tailored to various crops. However, the computational expertise and time required for data analysis remain limitations, especially in time-sensitive marker-assisted breeding. Nonetheless, the future of GBS looks promising with the emergence of more software packages and computational pipelines. Array-based genotyping platforms have also advanced, notably with the development of SNP arrays like the SoySNP50K iSelect BeadChip, facilitating high-throughput genotyping of soybean PI lines (Song et al., 2015). Further technological progress allows cost-effective resequencing of hundreds of lines, marking a new era in genotyping (Islam et al., 2022). The challenge now lies in effectively leveraging these resources for marker-assisted applications.

These innovations have caused a paradigm shift in the magnitude and importance of structural variations from the genome to the pan-genome of cereals (Della Coletta et al., 2021). Many sequencing projects have been initiated, and genome assemblies for numerous plants have been accomplished. These innovations have transformed the crop biology and crop breeding approach against various stressors in the changing climatic scenario. However, this requires systems that allow accessions in gene banks to be linked easily to genomic data and the necessary resources to collect that data.

3.4.5.1 Insights from QTL Mapping and Genome-Wide Association Studies (GWAS)

Advanced genomic techniques like quantitative trait locus (QTL) mapping and genome-wide association studies (GWAS) have emerged as effective tools for unraveling the genetical aspect of stress tolerance in vegetable crops. By identifying

Table 3.3 Genes controlling various biotic and abiotic stresses in crops

Crops	Gene	Trait	References
Potato	<i>StbZIPs</i>	Due to their dysregulation, <i>StbZIPs</i> may be essential in a variety of abiotic stress situations	Kumar et al. (2021)
Maize	<i>ZmbZIP4</i>	<i>ZmbZIP4</i> has a role in maize root growth and is a positive regulator of plant responses to abiotic stress	Ma et al. (2018)
Maize	<i>DREB2</i>	Dehydration-responsive element-binding genes for salt and drought tolerance	Akbudak et al. (2018)
Wheat	<i>TaZIP14-B</i>	In transgenic plants, a new wheat C-bZIP gene called <i>TabZIP14-B</i> contributes to freezing and salt tolerance	Zhang et al. (2017)
Rice	<i>Xa21</i>	<i>Xa21</i> gene for broad-spectrum resistance to bacterial blight	Liu et al. (2021)
Rice	<i>Lr34</i>	<i>Lr34</i> gene for durable resistance against multiple fungal pathogens	Sucher et al. (2018)
Soybean	<i>G10-EPSPS</i>	5-Enolpyruvylshikimate-3-phosphate synthase gene for glyphosate (herbicide) resistance	Xiao et al. (2019)
Tomato	<i>SlERF5</i>	Reducing the impact of salinity and drought	Bhat et al. (2024)
<i>Arabidopsis thaliana</i> (Thale cress)	<i>AtMYB49</i>	Based on the results, <i>AtMYB49</i> genetic modification may offer a fresh strategy for enhancing plants' ability to withstand salt	Zhang et al. (2020)
Apple	<i>MdWRKY100</i>	Studies show that <i>MdWRKY100</i> is a positive regulator of apple resistance to <i>Colletotrichum gloeosporioides</i>	Ma et al. (2021)

key genes and genomic regions associated with tolerance to various stresses, breeding programs are planned for developing resilient and high-yielding cultivars (Table 3.3). In tomatoes, over 20 resistance genes have been either mapped or cloned against various bacterial, fungal, viral, and nematode diseases (Simko et al., 2021). Moreover, numerous studies have investigated genes or QTLs associated with abiotic stresses like salt, cold, heat, and drought in vegetable crops (Table 3.4) (Simko et al., 2021). Utilizing identified QTLs, mainly from wild tomato species, in the breeding has been challenging, stalling progress in creating abiotic stress-tolerant tomato varieties.

3.4.5.2 Marker-Assisted Selection (MAS)

Breeding crops for stress tolerance is greatly aided by marker-assisted selection (MAS), which makes it feasible to identify the genes and molecular markers linked to particular stress response mechanisms (Table 3.4). However, the advent of high-throughput genetic markers like PCR-based markers and SNPs improved MAS for various vegetable crop improvement (Fig. 3.5). The verification and applicability of markers in breeding remain variable, although MAS is commonly used, especially

Table 3.4 QTL mapped genes against various abiotic and biotic stressors

Plant stress	Marker-assisted selection (MAS) role	Crop example	References
Drought stress	Identification of genes related to water use efficiency, osmotic adjustment, and root architecture. Accelerated selection of drought-tolerant individuals. QTL, “Qncl. Sw1,” is linked to grain yield	Maize (<i>Zea mays</i>)	Sandhu et al. (2023)
Heat stress	Identification of heat shock proteins, antioxidant enzymes, and other heat tolerance mechanisms. Faster breeding of heat-tolerant varieties. HD2733 used as a genetic resource	Wheat (<i>Triticum aestivum</i>)	Bellundagi et al. (2022)
Salinity stress	Discovery of genes involved in ion transporters, osmoprotectants, and salt exclusion mechanisms. Enhanced breeding of salt-tolerant cultivars. YNU31-2-4 highly tolerant to salt stress	Rice (<i>Oryza sativa</i>)	Rana et al. (2019)
Pest resistance	Identification of insect resistance genes and biochemical pathways related to pest defense mechanisms. Improved selection of pest-resistant plants. Bph1 and Bph2 resistance genes of rice	Rice (<i>Oryza sativa</i>)	Kumari et al. (2022)
Disease resistance	Discovery of genes conferring resistance to fungal, bacterial, and viral pathogens. Facilitated breeding of disease-resistant varieties. Bs1, Bs2, and Bs3 resistance genes of pepper	Tomato (<i>Solanum lycopersicum</i>) and pepper (<i>Capsicum annuum</i>)	Simko et al. (2021)
Nutrient stress	Identification of genes related to nutrient uptake, utilization, and transport. Enhanced breeding of nutrient-efficient crops	Rice (<i>Oryza sativa</i>)	Fiaz et al. (2021)

for incorporating multiple disease resistance traits (Simko et al., 2021). To mitigate drought stress MAS enables breeders to identify genes linked to root architecture, osmotic adjustment, and water use efficiency. This enables the selection of drought-tolerant individuals in crops like rice and maize to proceed more quickly. In a similar vein, MAS facilitates the rapid breeding of heat-tolerant varieties, especially in wheat and soybean, by assisting in the identification of heat shock proteins and antioxidant enzymes essential for heat tolerance (Yadav et al., 2022). Breeders can effectively screen breeding populations and choose individuals with desired stress tolerance traits by using MAS. This will ultimately increase crop productivity and resilience in the face of unfavorable environmental conditions.

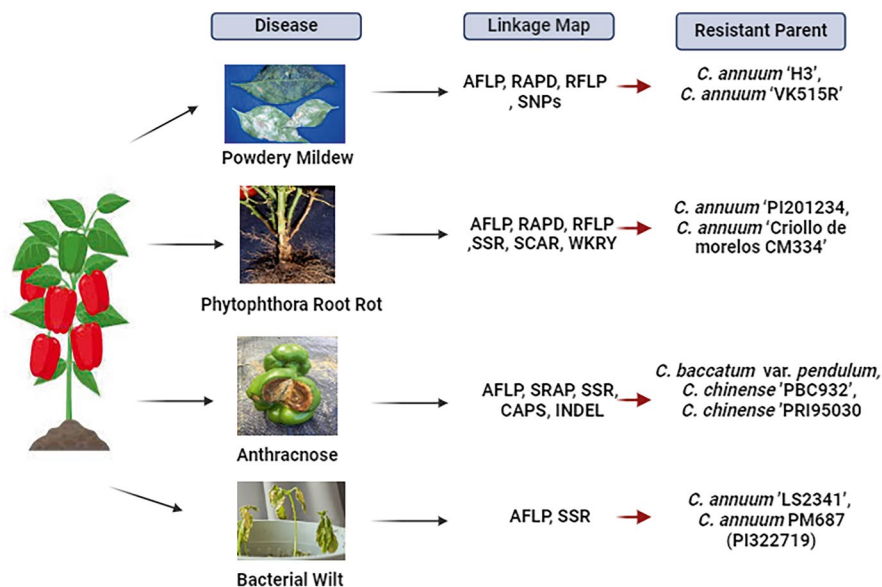


Fig. 3.5 Marker-assisted selection (MAS) against various diseases in *Capsicum* spp.

3.4.5.3 Genome Selection

Genome selection uses genomic analysis to find and select plants with desired genetic traits, like improvement of tolerance against stress. Through the strategic use of genetic diversity, breeders can create crop varieties resilient to various stresses, such as diseases, salinity, drought, and extreme temperatures (Lebedev et al., 2020). Compared to conventional methods, genome selection accelerates crop breeding and allows for targeted crop improvement. For instance, genome selection helps breeders find plants with advantageous genetic variations related to stress response mechanisms, root architecture, and water use efficiency in the context of drought tolerance. Breeders can identify genomic regions linked to drought tolerance traits by analyzing genomic data from various germplasm collections. They can then utilize this information to identify and cross plants with the most promising genetic backgrounds. This strategy has been effectively used for crops like wheat, rice, and maize, resulting in the creation of drought-tolerant cultivars that can continue to be produced under water-scarce circumstances (Nepolean et al., 2018). By identifying and choosing plants that naturally possess a genetic resistance to pathogens, genome selection can also be used to improve crop disease resistance. Breeders choose plants having desired resistance traits by using molecular markers linked to genes encoding disease resistance by analyzing genomic data from resistant and susceptible plants. This method has helped to improve yield stability and lessen reliance on chemical inputs for disease control by breeding crops with increased resistance to diseases like wheat rust, rice blast, and soybean cyst nematode (Yin & Qiu,

2019). Genome selection is a potent tool for managing stresses in various crops, allowing breeders to create hardy cultivars that can endure harsh environmental conditions and support global food security.

3.4.6 *Transgenic Technology*

Transgenic technology, which introduces genes from diverse sources that confer resilience to biotic and abiotic stresses, has been instrumental in bolstering stress tolerance in various crops (Table 3.3). The creation of transgenic crops with herbicide tolerance is one noteworthy example. Farmers can effectively control weed growth without harming their crops by introducing genes encoding enzymes that confer resistance to specific herbicides, like glyphosate, into crops like soybean, maize, and cotton. This increases productivity and decreases the need for manual weed management techniques. Similar to this, transgenic techniques have been used to introduce genes encoding insecticidal proteins derived from *Bacillus thuringiensis* (Bt) bacteria to increase tolerance to insect pests (Jurat-Fuentes et al., 2021). Genetically modified crops, including corn, cotton, and eggplant, release Bt toxins that specifically target pests like corn borers, cotton bollworms, and eggplant fruit borers. Transgenic crops with these proteins expressed in their tissues have an inherent resistance to insect damage, which lowers the need for chemical insecticides and minimizes yield losses from pest infestations.

Furthermore, transgenic technology provides ways to improve crop resistance to abiotic stressors. For example, scientists have created drought-tolerant transgenic crops by introducing genes that encode proteins that participate in stress signaling pathways, water transport, and osmotic regulation. Similar to this, crops have been modified to confer tolerance to these harsh environmental conditions by incorporating genes from extremophilic organisms that can thrive in salinized soils or extremely high temperatures (Rao et al., 2022). Crop scientists are using transgenic techniques to investigate novel approaches for creating stress-tolerant crops that can endure the harsh effects of climate change and ensure food security for an expanding world population.

3.4.7 *Genome Editing*

CRISPR-Cas9 and other genome editing technologies enable precise modifications to crop genomes, causing a paradigm shift in crop stress management. By addressing major issues like salinity, temperature extremes, diseases, and drought, these techniques provide focused interventions to improve stress tolerance in different crops (Table 3.5). The possibility to create resilient crop varieties that can flourish in harsh environmental circumstances can be unlocked by researchers through precise editing of genes linked to stress responses. Numerous food crops, including

Table 3.5 Genome editing strategies for crop improvement against abiotic and biotic stresses

Crop	Genome editing technique	Stress addressed	References
Maize (<i>Zea mays</i>)	CRISPR-Cas9 targeting genes related to root architecture and water use efficiency	Drought stress	Kořínková et al. (2022)
Wheat (<i>Triticum aestivum</i>)	CRISPR-Cas9 targeting genes encoding heat shock proteins and antioxidant enzymes	Heat stress	Trono and Pecchioni (2022)
Rice (<i>Oryza sativa</i>)	CRISPR-Cas9 targeting genes involved in ion transporters and osmoprotectants	Salinity stress	Shelake et al. (2022)
Potato (<i>Solanum tuberosum</i>)	CRISPR-Cas9 editing for insertion of resistance genes Rpi-blb1 and Rpi-blb2	Disease resistance	Kieu et al. (2021)
Soybean (<i>Glycine max</i>)	CRISPR-Cas9 targeting genes (GmUGT) associated with pest susceptibility	Pest resistance	Zhang et al. (2022a)
Tomato (<i>Solanum lycopersicum</i>)	CRISPR-Cas9 editing to alter ethylene pathway genes (lncRNA1459) for delayed fruit ripening	Post-harvest stress	Li et al. (2018)
Cotton (<i>Gossypium hirsutum</i>)	CRISPR-Cas9 targeting genes (lncRNA) for insecticidal proteins	Pest resistance	Zhang et al. (2022b)
Barley (<i>Hordeum vulgare</i>)	CRISPR-Cas9 targeting genes related to water use efficiency and osmotic regulation	Drought stress	Robertson et al. (2021)
Sorghum (<i>Sorghum bicolor</i>)	CRISPR-Cas9 targeting genes associated with heat shock proteins and photosynthetic efficiency	Heat stress	Mondal et al. (2023)
Citrus (<i>citrus</i> spp.)	CRISPR-Cas9 targeting genes (CsWRKY22) involved in citrus canker response	Disease resistance	Wang et al. (2019)
Alfalfa (<i>Medicago sativa</i>)	CRISPR-Cas9 targeting genes related to ion transport and osmotic regulation	Salinity stress	Hrbáčková et al. (2020)

vegetable crops (*Brassica oleracea*, *Daucus carota*, *Cucurbita pepo*, *Solanum lycopersicum*, *Solanum tuberosum*, *Cucumis sativus*, *Ipomoea batatas*, *Ocimum basilicum*, *Manihot esculenta*, *Capsicum*, and *Lactuca sativa*) and fruit crops (*Citrullus lanatus*, *Actinidia deliciosa*, *Vaccinium*, *Citrus*, *Carica papaya*, *Pyrus*, *Musa*, *Cocos nucifera*, *Phoenix dactylifera*, *Vitis*, and *Litchi chinensis*), have been reported to have undergone genome editing. In addition, other industrial crops, viz., cereal crops (*Hordeum vulgare*, *Oryza sativa*, *Triticum*, *Zea mays*, and *Avena*), legume crops (*Cicer arietinum*, and *Vigna unguiculata*), sugar-producing crops (*Saccharum officinarum*, and *Beta vulgaris*), spice crops (*Piper nigrum*, and *Crocus sativus*), and oil crops (*Brassica napus*, *Linum usitatissimum*, *Elaeis guineensis*, *Glycine max*, and *Helianthus annuus*), have also been worked out for genome editing to develop stress resistance or tolerance. For example, genome editing enables the modification of genes involved in water uptake, retention, and utilization to combat drought stress. Improved drought tolerance and productivity are demonstrated by edited crops, which minimize transpiration loss and maximize water transport efficiency in water-limited environments (Sami et al., 2021). Similarly, by focusing on

susceptibility genes and boosting plant immunity, genome editing presents opportunities to strengthen crops against pathogens. Edited crops exhibit improved resistance to diseases like citrus canker, wheat powdery mildew, and rice blast by introducing novel resistance traits or disrupting genes targeted by pathogens, protecting yield and quality (Rato et al., 2021).

Moreover, genome editing offers opportunities to improve crop resistance to temperature fluctuations and salinity stress. Scientists can create crops that can withstand harsh temperature swings and saline soils through gene modification related to ion transport, osmotic regulation, and thermal regulation (Núñez-Muñoz et al., 2022). Genome-edited crops can potentially alter the detrimental impact of environmental stresses through targeted genetic interventions to ensure sustainable production and global food security in the changing climate.

3.5 Future Prospects

Breeding technologies have great potential to improve crop stress management by providing creative answers to the problems caused by environmental pressures and climate change. The prospects include the efficient and accurate utilization of state-of-the-art genomic tools like genome editing and marker-assisted selection to hasten the genetic diversification in crops that can withstand stress. Furthermore, deeper comprehension of crop stress response mechanisms will be made possible by advances in omics technologies, such as transcriptomics, metabolomics, and proteomics, which will make it easier to find novel genetic targets for crop improvement. Furthermore, multidisciplinary approaches can potentially enhance crop resilience by unlocking synergistic effects, utilizing microbial symbionts for stress mitigation, and combining genetic engineering with conventional breeding methods. Breeders and researchers have never-before-seen opportunities to create stress-tolerant crops that guarantee sustainability, global food security, and resilience in the face of new challenges thanks to breeding technologies that are still developing.

3.6 Challenges and Economic Significance

Reducing stress in agriculture is a complex task with substantial financial consequences for farmers and breeders. It is difficult for breeders to navigate the regulatory frameworks surrounding emerging breeding technologies while simultaneously identifying and effectively incorporating stress-tolerance traits into crop varieties. There are also ongoing challenges due to the intricacy of stress interactions and the requirement for constant adaptation to changing environmental conditions. Farmers may experience decreased profitability, higher input costs, and yield reduction in managing stressors like pests, diseases, and drought. However, there is a chance to increase resilience, yield stability, and financial returns using crop varieties that can

withstand stress. For farmers and breeders alike, striking a balance between the financial sustainability of crop production and the investment in stress management techniques is still a major concern.

3.7 Conclusion

Many wild plants lose their natural habitat systems due to crop domestication and other agricultural revolutions aimed to meet the growing demand for food due to human preferences and changing environmental conditions. This causes cultivation bottlenecks, which in turn result in domesticated crops that are inefficient. Thus, there are many landraces of various crops that remain untapped and undomesticated during the expansion of high-yielding cultivars and chemical-based farming. These landraces and wild genotypes can be sources of high genetic diversity and stability under the evolving environment and pathogenic races; however, these need to be screened out for resistance or tolerance using cutting-edge high-throughput technologies and advanced breeding approaches as described earlier. This is because the rising world population and the effects of climate change are pushing agricultural productivity to the limit. To effectively manage stress in the face of today's obstacles, an integrated strategy including advanced selection or breeding approaches using wild and local genotypes and raising public awareness about the importance of transgenic crops regarding environment and health safety must be implemented. The future will involve the development of tolerant varieties through diverse populations, affordable SNP profiling, molecular breeding, QTL mapping, DNA methylation, overexpression or knockdown, and CRISPR-mediated genome editing. Collaborative advances in functional, comparative, and structural genomics should be incorporated into traditional molecular and breeding approaches to enhance the performance of tolerant varieties. Comparative genomics is anticipated to offer scope for creating tolerant cultivars that are highly adapted to coexisting abiotic stresses.

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Chapter 4

Advanced Mutagenesis Techniques for Climate Resilient Crops



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4.1 Background

The frequent climatic change events, such as temperature fluctuations, unpredictable intensity and pattern of rainfall, changing composition of atmospheric gases, etc., have led to a reduction of 15–25% in agriculture income. Rising global temperatures are a significant concern for humanity, with the potential to affect stable food crops. Climate change has intensified environmental stresses like drought and salt stress, along with biotic stresses. These combined challenges, along with the increasing food demands from a rapidly increasing worldwide population, present a significant risk to food security worldwide, thus necessitating the importance, development, and utilization of climate-resilient agriculture.

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Table 4.1 Comparison of random versus targeted mutagenesis techniques

Properties	Random mutagenesis	Targeted mutagenesis
Purpose	Generate diverse mutations across the entire genome	Introduce specific mutations at precise locations in the genome
Approach	Induce mutations randomly using mutagens such as x-rays, gamma irradiation, EMS, and UV radiation	Enables direct editing of DNA at specific sites using techniques like CRISPR Cas9, TALENs, or ZFNs
Scope of mutation	Broad, affecting multiple genes or regions randomly	Precise, targeting specific genes or nucleotides
Efficiency	Low efficiency due to randomness	High efficiency with specific targeting
Control	Limited control over mutation sites and types	High control, enabling manipulation of specific genomic regions
Applications	Useful for generating diversity in genetic studies or directed evolution experiments	Useful for precise modification of genes for functional analysis or gene therapy

However, the challenge of development of stress resilience under varied environments has been a difficult task due to low heritability of traits. Therefore, plant breeders are actively working to identify additional characteristics that can create tolerance to various abiotic stressors. Strengthening crop resilience to climate change is vital for ensuring food and nutritional security. This objective can be accomplished by generating novel genetic variations. Climate resilience is considered a fundamental component of sustainable agriculture. Plant scientists employ various strategies for mutation induction, utilizing different mutagenic compounds, both physical and chemical. But nontargeted mutagenesis approach involves the introduction of random mutations across the genome without specific targeting of genes or regions. Nontargeted mutagenesis induces genetic changes throughout the genome, leading to a broader spectrum of mutations. Random mutagenesis approaches are being utilized for the improvement of various crops (Sharma et al., 2020; Sharma & Thakur, 2021a, b; Sharma et al., 2024; Sharma et al., 2022; Maan et al., 2023), whereas this approach may lack precision or be unpredictable in nature as compared to targeted mutagenesis.

In contrast, advanced or targeted mutagenesis involves precisely targeting specific genes or genomic regions to induce desirable changes. The advanced mutagenesis tools enable scientists to edit the DNA sequences at precise locations, allowing for the induction of precise mutations or modifications with high accuracy (Table 4.1). Advanced approaches such as CRISPR-Cas9, TALENs, and ZFNs are commonly employed for precise genome modifications. Targeted mutagenesis approaches have evolved with time, leading to more precise modifications in the genome of an organism (Fig. 4.1). This chapter provides an overview of advanced mutagenesis approaches, basic concepts, and their recent application tools in the development of climate-resilient crops.

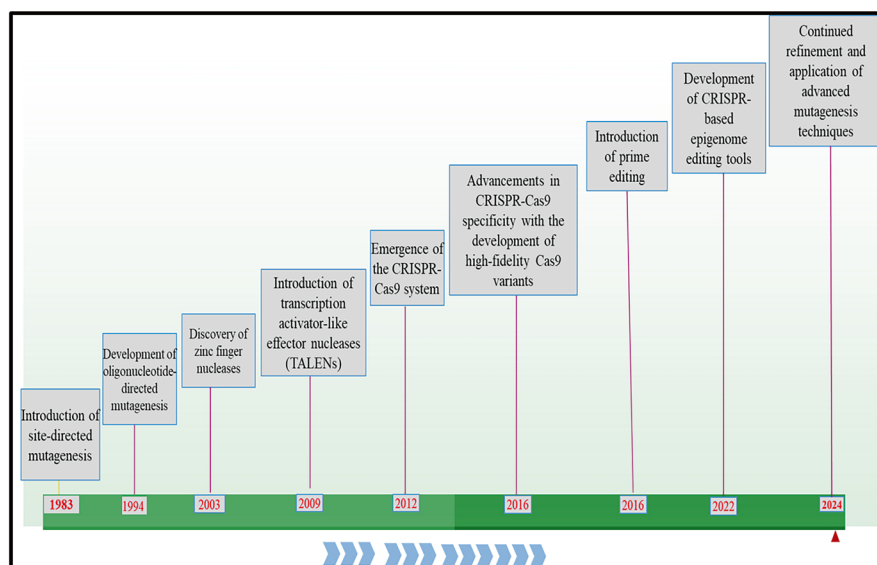


Fig. 4.1 Evolution and timeframe of targeted mutagenesis techniques

4.2 Abiotic Stresses

Abiotic stressors that significantly limit worldwide crop productivity include salt, drought, high heat and cold, nutritional imbalances, and flooding. Extreme temperatures are a major concern for agriculture worldwide, impacting crop productivity and food security. High temperatures, drought, and soil salinization directly affect plant development and yield. Similarly, frost events or prolonged cold spells during the growing season can cause tissue damage, leading to yield losses and reduced crop quality. This shift in temperature regimes also affects pest and disease dynamics. Additionally, increased CO₂ levels are expected to lower the nutritional content of crops.

Over 70 million hectares of rice cultivating areas are impacted by drought stress, and over 100 million hectares of agriculture land are unfit for cultivation due to salt and nutrient stress. These conditions lead to lower yields and have a detrimental effect on human nutrition. Developing crops with improved tolerance to environmental factors such as increased temperatures, drought, and soil salinization is crucial for safeguarding agricultural productivity and ensuring sustainable crop production for the increasing global population. In this context, induced mutagenesis serves as an effective tool to tackle the challenges brought about by rising temperatures, heat waves, prolonged cold or freezing conditions, and limited water resources.

4.3.1 CRISPR/Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats)

CRISPR/Cas9 platform (Jinek et al., 2012) has revolutionized targeted mutagenesis breeding by offering precise genome modifications with unprecedented efficiency and higher accuracy at faster speed. This technology enables breeders to simultaneously target multiple genes responsible for desired traits. This strategy has made it easier to create genotypes that are more resilient to a number of environmental stressors, such as heat, cold, salinity, drought, and flooding.

Overall, CRISPR/Cas9 process involves designing a guide RNA (gRNA) sequence tailored to target a specific gene within the plant’s genome. This gRNA, in combination with the Cas9 enzyme, is introduced into plant cells using techniques like *Agrobacterium*-based transformation or biolistic delivery. After entering the cell, Cas9-guideRNA complex looks for the target sequence in the genome before causing a double-strand break (DSB) at the designated spot. DNA repair methods, namely homology-directed repair (HDR) and nonhomologous end joining (NHEJ), enable genetic modifications. These modifications can be specific insertions or deletions, or they can be minor insertions or deletions (indels). Transformed cells are then screened to identify those with the desired modifications, which are subsequently regenerated into whole plants through tissue culture techniques. Table 4.2 lists the genes that are targeted by CRISPR/Cas9-based editing for the establishment of stress tolerance in plants. These genes include those related to drought, salt, heat, and cold stress, as well as their negative regulators.

Table 4.2 Representative examples of CRISPR/Cas9 mediated improvement in crops for abiotic stress tolerance

Abiotic stress/ target trait	Crop	Target gene	Transformation method	References
Cold tolerance	<i>Arabidopsis thaliana</i>	<i>UGT79B2</i>	<i>Agrobacterium</i> mediated floral dip	Li et al. (2017a, b)
		<i>AtCBF1, AtCBF2</i>	<i>Agrobacterium</i> mediated	Chen et al. (2010)
	<i>Solanum lycopersicum</i>	<i>SlCBF1</i>	<i>Agrobacterium</i> mediated	Li et al. (2018)
	<i>Oryza sativa</i>	<i>OsAnn3, OsAnn5</i>	<i>Agrobacterium</i> mediated	Shen et al. (2017)
		<i>OsPIN5b, GS3, OsMYB30</i>	<i>Agrobacterium</i> mediated	Zeng et al. (2020)
		<i>OsPRP1</i>	<i>Agrobacterium</i> mediated	Nawaz et al. (2019)

(continued)

Table 4.2 (continued)

Abiotic stress/ target trait	Crop	Target gene	Transformation method	References
Heat tolerance	<i>Gossypium hirsutum</i>	<i>GhPGF, GhCLA1</i>	Agrobacterium mediated	Li et al. (2021a)
	<i>Zea mays</i>	<i>ZmTMS5</i>	Particle bombardment	Li et al. (2017a, b)
	<i>Lactuca sativa</i>	<i>LsNCED4</i>	Agrobacterium mediated	Bertier et al. (2018)
	<i>Solanum lycopersicum</i>	<i>SIBZR1</i>	Agrobacterium mediated	Yin et al. (2018)
		<i>SIMAPK3</i>	Agrobacterium mediated	Yu et al. (2019)
	<i>Oryza sativa</i>	<i>OsHSA1</i>	Agrobacterium mediated	Qiu et al. (2018)
		<i>OsPYL1/4/6</i>	Agrobacterium mediated	Miao et al. (2018)
		<i>OsPDS</i>	Gene gun	Nandy et al. (2019)
		<i>OsNAC006</i>	PEG-mediated	Wang et al. (2020)
Salinity	<i>Glycine max</i>	<i>GmDrb2a, GmDrb2b</i>	Agrobacterium mediated	Curtin et al. (2018)
		<i>GmA1TR</i>	Agrobacterium mediated	Wang et al. (2021)
	<i>Oryza sativa</i>	<i>OsRR22</i>	Agrobacterium mediated	Zhang et al. (2019)
		<i>OsRAV2</i>	Agrobacterium mediated	Duan et al. (2016)
		<i>OsAGO2</i>	Agrobacterium mediated	Yin et al. (2020)
		<i>OsNAC45</i>	Agrobacterium mediated	Zhang et al. (2020)
		<i>OsVDE</i>	Agrobacterium mediated	Wang et al. (2003)
		<i>OsSAPK2</i>	Agrobacterium mediated	Lou et al. (2017)
	<i>Arabidopsis thaliana</i>	<i>UGT79B2, UGT79B3</i>	Agrobacterium mediated	Li et al. (2017a, b)
		<i>AtWRKY, AtWRKY4</i>	Agrobacterium mediated	Li et al. (2021a, b)
	<i>Medicago truncatula</i>	<i>MtHEN1</i>	Agrobacterium mediated	Curtin et al. (2018)
	<i>Triticum aestivum</i>	<i>TaHAG1</i>	Agrobacterium mediated	Zheng et al. (2021)
	<i>Solanum lycopersicum</i>	<i>SlHyPRP1</i>	PEG-mediated	Tran et al. (2021)
		<i>StCoilin</i>	PEG-mediated	Makhotenko et al. (2019)

(continued)

Table 4.2 (continued)

Abiotic stress/ target trait	Crop	Target gene	Transformation method	References
Drought	<i>Glycine max</i>	<i>GmDrb2b</i>	Agrobacterium mediated	Curtin et al. (2018)
	<i>Solanum lycopersicum</i>	<i>SIMAPK3</i>	Agrobacterium mediated	Wang et al. (2017)
	<i>Arabidopsis thaliana</i>	<i>MIR169a</i>	Agrobacterium mediated	Zhao et al. (2016)
	<i>Arabidopsis thaliana</i>	<i>UGT79B3</i>	Agrobacterium mediated	Li et al. (2017a, b)
	<i>Oryza sativa</i>	<i>OsDST</i>	Agrobacterium mediated	Kumar et al. (2020)
	<i>Zea mays</i>	<i>ARGOS8</i>	Particle bombardment	Shi et al. (2017)
	<i>Brassica napus</i>	<i>BnaA6.RGA</i>	Agrobacterium mediated	Wu et al. (2020)
	<i>Cicer arietinum</i>	<i>At4CL, AtRVE7</i>	PEG-mediated	Badhan et al. (2021)
	<i>Triticum aestivum</i>	<i>TaDREB2, TaDREB3, TaERF3</i>	PEG-mediated	Kim et al. (2018)
	<i>Medicago truncatula</i>	<i>MtHEN1</i>	Agrobacterium mediated	Curtin et al. (2018)

4.3.1.1 Cold Stress Tolerance

Low temperature stress adversely affects plant health, development, and productivity (Jha et al., 2017). Among the advanced mutagenesis tools available, CRISPR toolkit offers an effective method for developing transgene-free plants with modified genomes. This method presents the best solution for mitigating the effects of low temperature stress to ensure food security (Mo et al., 2020). For instance, in rice, CRISPR-mediated knockout of negative regulator transcription factors can enhance cold tolerance.

One such transcription factor, “*OsMYB30*,” interferes with the β -amylase gene promoter and impairs the ability to withstand cold. When exposed to cold stress, “*OsMYB30*” combines with “*OsJAZ9*” to produce a complex that inhibits the production of the β -amylase gene. This inhibition affects the breakdown of starch and the accumulation of maltose, which may make you more sensitive to cold (Lv et al., 2017). Simultaneous mutations in the genes “*OsPIN5b*,” “*GS3*,” and “*OsMYB30*” produced enhanced yield and greater resistance to cold stress by CRISPR/Cas9-mediated genome editing (Zeng et al., 2020). Similarly, employing CRISPR/Cas9 to disable “*UGT79B2*” in *Arabidopsis* resulted in a notable up-regulation of genes that respond to chilling stress (Li et al., 2017a, b). Moreover, rice’s disruption of “*OsPRPI*” increased its vulnerability to cold; mutant lines showed lower antioxidant enzyme activity as well as lower levels of proline, chlorophyll, abscisic acid, and ascorbic acid (AsA) in colder temperatures than did wild-type species. The

protective effect of C-repeat binding factor 1 (*CBF1*) against chilling/cold damage in tomatoes has been shown by CRISPR/Cas9-based mutants targeting the “*cbf1*” gene, resulting in decreased electrolyte leakage. Additionally, these mutant plants have increased amounts of indole-3-acetic acid and hydrogen peroxide, which helps tomatoes withstand cold stress better (Chen et al., 2015). However, strawberries with CRISPR/Cas9 mediated mutations provided reduced tolerance to cold, indicating that “*FvICE1*” gene acts as a positive regulator of low temperature stress in strawberries (Han et al., 2023).

4.3.1.2 Heat Stress Tolerance

A major abiotic stressor, heat stress poses a considerable obstacle to agricultural production. During high temperature stress, plants initiate intricate molecular networks that involve the activation of genes that respond to thermal stress, signal transduction pathways, and metabolite production (Jha et al., 2017). Among genome modification approaches, CRISPR/Cas9 stands out as a revolutionary method for specific genome manipulation, enabling the study of molecular networks linked with high temperature stress and enhancing resistivity (Duan et al., 2016). Tomato is an excellent plant for CRISPR/Cas9-mediated gene modification due to its efficient transformation capability. Recently, CRISPR/Cas9-mediated modification of the heat-susceptible gene “*SIAGAMOUS-LIKE 6*” in tomato has been developed to improve heat tolerance, resulting in better fruit set under thermal stress conditions (Klap et al., 2017).

The genome editing of “*SLMAPK3*” mutant tomatoes using CRISPR/Cas9 revealed increased thermotolerance in these plants when compared to wild types, suggesting that “*SLMAPK3*” is a negative controller of thermotolerance (Yu et al., 2019). “*BRZI*” gene also promotes heat tolerance by acting as a positive regulator of reactive oxygen species (ROS). This was verified by editing “*bzr1*” mutants using CRISPR/Cas9; these mutants showed poor heat tolerance because of decreased Respiratory Burst Oxidase Homolog 1 (RBOH1) activity and decreased H₂O₂ generation in the apoplast (Yin et al., 2018). In a similar vein, tomatoes with CRISPR/Cas-mediated mutants targeting the “*HSA1*” (*heat-stress sensitive albino 1*) gene showed more thermal stress sensitivity than wild plant species (Qiu et al., 2018).

Improved thermosensitive male-sterile plants of maize were produced by CRISPR mutants that targeted the *thermosensitive genic male-sterile 5* (*TMS5*) gene (Li et al., 2017a, b). Higher temperatures promoted seed germination in lettuce when “*NCED4*” enzyme involved in abscisic acid (ABA) production was knocked off. *LsNCED4* mutants are highly valuable commercially in hot manufacturing environments (Bertier et al., 2018).

4.3.1.3 Drought Stress Tolerance

It has been demonstrated that overexpressing transcription factors and genes responsive to drought in plant genotypes increases signaling molecules and accumulates metabolic products to improve drought tolerance. Elevated drought tolerance has been observed with the overexpression of “*AREB1*,” while “*AREB1*” knock-out mutants displayed increased sensitivity to drought stress (Singh & Laxmi, 2015). Tomatoes with improved drought tolerance relative to overexpressing transgenic and wild-type plants were produced by precise mutagenesis of the lateral organ boundaries domain TF “*SILBD40*” using CRISPR/Cas9. Tomatoes’ resistance to drought was further improved by CRISPR/Cas9 deletion of “*SILBD40*” (Liu et al., 2020). Additionally, CRISPR/Cas9-edited tomato mutants lacking the “*SIMAPK3*” gene exhibited heightened responses to drought stress. These mutant lines showed severe wilting, increased levels of H_2O_2 , reduced antioxidant levels, and enhanced membrane damage in drought conditions (Wang et al., 2017).

In *Arabidopsis*, it has been reported that the CRISPR/dCas9 merger with a *Histone Acetyl Transferase (HAT)* gene enhances drought stress resistance (Roca Paixão et al., 2019). The *OsSAPK2* gene is necessary for ABA-mediated stress resistance in rice. *OsSAPK2* loss-of-function mutations developed by CRISPR/Cas9 resulted in mutant plants that were more sensitive to drought than wild-type plant species (Lou et al., 2017). Similarly, CRISPR/Cas9-based mutations in the gene coding for “*OsDST*” in rice facilitated an enhanced stomatal response compared to wild-type plants. In *Arabidopsis*, in comparison to the wild type, mutants with CRISPR/Cas9-mediated genetic changes in gene coding for *OPEN STOMATA 2 (OST2)* had a higher level of stomatal closure and an improved stomatal response (Osakabe et al., 2016). When compared to wild-type plants, genome-edited lines containing *SRL1* and *SRL2* mutant lines showed a variety of abnormalities, including variations in stomatal behavior, number, chlorophyll content, vascular bundles, conductance, transpiration rate, and many more agronomic parameters (Liao et al., 2019).

4.3.1.4 Salinity Tolerance

Salinity stress induces different physiological and morphological variations in plants by altering gene expression levels and signaling networking (Prusty et al., 2018). Researchers have identified and characterized several genes using CRISPR/Cas genome modification to enhance plant salinity tolerance. For instance, knocking out the “*AtWRKY3*” and “*AtWRKY4*” genes in *Arabidopsis thaliana* with CRISPR/Cas9 led to a notable increase in gene expression under salt stress. Whereas, these double mutants were more sensitive to saline conditions, showing

increased ion leakage and decreased antioxidant activity (Chen et al., 2021). Additionally, the role of the “*AtACQOS*” gene in acquired osmotolerance and its importance in salt stress tolerance in *Arabidopsis* was studied using CRISPR-generated mutants (Kim et al., 2021).

Salt stress tolerance in soybeans (*Glycine max*) has been demonstrated to be conferred by CRISPR/Cas9-based knockout mutants of the genes encoding *abscisic acid-induced transcription repressors* (*AITRs*) (Wang et al., 2021). Likewise, soybeans with *GmDrb2a* and *GmDrb2b* gene knockout mutants showed improved resistance to salinity stress (Curtin et al., 2018). Lou et al. (2017) reported salt stress tolerance in rice by *SnRK2* knockout mutants and osmotic stress/ABA-activated protein kinases *SAPK-1* and *SAPK-2* genes. CRISPR mutants targeting genes such as *OsDST*, *OsNAC45*, *ARGONAUTE2* (*AGO2*), Rice type-B response regulator *OsRR22*, and *OsBBS1* were also developed in rice to enhance salt stress tolerance (Kumar et al., 2020). In wheat, CRISPR/Cas9-generated knock-out mutants of the *TaHAG1* gene exhibited improved salinity tolerance (Zheng et al., 2021). Furthermore, by concentrating on the *OsbHLH024* gene, researchers created rice mutants with modified DNA to study the gene’s function in salt stress. Under salt stress, the *OsbHLH024* mutants’ complete chlorophyll content and plant biomass were markedly improved by the removal of a single nucleotide base (Alam et al., 2022).

4.3.2 ZFN

Developed in 2003, zinc finger nuclease (ZFN) technology uses designed nucleases to achieve precise genome editing. Zinc finger proteins that bind to specific sites in DNA are fused with a nonspecific DNA cleavage domain that is obtained from the Fok I endonuclease to form ZFNs (ZFPs) (Guo et al., 2010). Derived from *Flavobacterium okeanokoites*, the endonuclease Fok I consists of a C-terminal domain that cleaves DNA nonspecifically and an N-terminal domain that binds DNA. By applying double-strand breaks (DSBs) at particular locations in the genome, ZFNs are employed in genome editing. When a homologous DNA template is available, these DSBs can result in gene disruption via mutagenesis brought on by nonhomologous end joining (NHEJ) repair or gene alteration by homologous recombination (HR). A ZFN-based targeted mutagenesis experiment’s essential phases are locating the gene of interest’s ZFN-binding site and creating ZFNs that can specifically target that location. The technology known as zinc finger nuclease (ZFN) has shown considerable promise in the breeding tool for increasing abiotic stress tolerance and has proven to be highly efficient in genome editing. Originally, transgenic *Arabidopsis* plants were genetically altered to incorporate semi-palindromic targets for a particular QQR. ZFNs were used to evaluate the efficacy of ZFNs as site-specific mutagens. Heat shock response genes may be functionally knocked off by the examination of modified target sites brought on by QQR. The results imply that ZFNs’heat-shock-regulated expression might be modified to

produce functional gene knockouts in *Arabidopsis* more effectively. The usefulness of ZFN-mediated mutagenesis in *Arabidopsis* plants and transformed tobacco samples was demonstrated using the “GUS” reporter activation experiment. Significantly, ZFNs made it easier to find single-nucleotide replacements at the break location, demonstrating that ZFNs can be applied to plant cells to precisely and locally modify the genome. It may be possible to use a ZFN-based targeted mutagenesis strategy on a variety of plant species. With an 18 bp recognition sequence and occurring every 6.9×10^{10} (418) bp, the three-finger ZFNs offer sufficient specificity for plants with genome sizes $\leq 10^{10}$, such as maize, tomato, and rice. However, four-finger ZFNs that identify 24-bp sequences can be used to obtain a higher specificity. Since the ZFN-based targeted mutagenesis method is so effective, mutant individuals can be identified without the use of positive or negative selection strategies. A ZFN-based approach is probably going to be an effective way for targeted mutagenesis in most plant species, according to research on ZFN-mediated mutagenesis in *Arabidopsis* (Lloyd et al., 2005).

4.3.3 TALENs

Naturally occurring transcription activator-like effector (TALE) proteins are identified in the phytopathogenic bacterium *Xanthomonas*. DSBs in the genome caused by TALENs are usually repaired by nonhomologous end joining (NHEJ), which results in insertions or deletions at the break site. Additionally, homologous recombination (HR) using a donor DNA template can repair double-strand breaks (DSBs) and introduce significant insertions or single nucleotide alterations. TALENs have proven to be an effective tool for inducing sequence-specific mutations in a range of plants, e.g., barley (*Hordeum vulgare*), rice (*Oryza sativa*), tobacco (*Nicotiana tabacum*), and *Arabidopsis* (*Arabidopsis thaliana*). TALENs offer promising applications in enhancing plant resilience to the challenges posed by climate change. This technique allows targeting genes involved in resistance/tolerance to harsh environmental conditions like drought and salinity. TALENs can facilitate genetic modifications and thereby help in dwelling enhanced resistance or tolerance traits in plants to changing environmental conditions. TALENs are an effective method for genome mutagenesis, finding gene functions, and improving traits in maize. It has been observed that TALENs in rice produce a high frequency of heritable mutations that are passed down via T1 to T2 generations with Mendelian proportions. Eighteen percent of the mutations affected more than one base, and 70% of the changes were deletions. Between 4% and 30% of callus (T0) mutations were found; these mutations frequently led to chimeric, heterozygous, bi-allelic, and sporadically homozygous plants. In order to improve characteristics like biotic and abiotic stress mitigation, TALENs have been used to cause mutations in a variety of rice genes. Despite the laborious nature of constructing the DNA recognition motif for TALENs, reports demonstrated its direct applicability in rice improvement. Overall, the TALENs have the capability to take care of challenges created by climate change in

agriculture, by both enhancing plant resilience and improving the quality of crop-derived products.

4.3.4 ODM

Oligonucleotide-directed mutagenesis (ODM) is a potent genetic engineering technique used to induce precise and targeted mutations into a specific gene. This method utilizes a short, single-stranded oligonucleotide, referred to as the mutagenic primer, which is designed to induce the desired mutation within a particular DNA sequence. The mutagenic primer enables precise modification due to its unique binding to the predefined DNA sequence in the plant genome, except for a single base-pair change. Initially, the ODM technique was successful in bacterial, yeast, and mammalian systems, and it has gradually found application in plants since the late nineties (Villalobos-López et al., 2022). Optimization of oligonucleotide design can significantly impact the frequency of targeted alterations (Sauer et al., 2016). This technique has the potential for crop improvement by utilizing the plant's own genome to enhance tolerance to abiotic stresses such as heat, drought, and salinity, without introducing additional genetic material.

4.3.5 Agro-Infiltration “*Sensu Stricto*”

Agro-infiltration “sensu stricto” represents a powerful tool in plant mutagenesis, offering precise control over delivering genetic material into plant cells. This technique involves the direct infiltration of *Agrobacterium tumefaciens*, engineered to carry specific mutagenic constructs, into plant tissues. Upon infiltration, the bacterium transfers the desired genetic material, such as CRISPR/Cas9 components or mutagenic oligonucleotides, into the plant genome, facilitating targeted mutagenesis. Agro-infiltration versatility allows for the rapid generation of mutant plants with desired traits, bypassing the need for traditional breeding methods and potentially accelerating crop improvement efforts. However, while offering immense potential, careful optimization of parameters such as *Agrobacterium* strain selection, infiltration conditions, and genetic constructs is essential to ensure efficient mutagenesis while minimizing off-target effects. Additionally, rigorous regulatory oversight and thorough risk assessment are crucial to address biosafety issues associated with the commercialization of genetically modified organisms into natural environmental conditions. Overall, agro-infiltration “sensu stricto” represents a valuable approach in plant mutagenesis, poised to revolutionize crop breeding by enabling precise genetic modifications for enhanced agricultural productivity and sustainability.

4.3.6 *Reverse Breeding*

Reverse breeding represents a ground-breaking approach in plant mutagenesis, offering a novel paradigm for precise genetic manipulation and trait fixation. This innovative technique involves the creation of doubled haploid lines through the manipulation of meiosis, resulting in the generation of homozygous parental lines directly from heterozygous individuals. Through inducing recombination events in a controlled manner, reverse breeding allows for chromosome segregation, effectively uncoupling desired traits from undesirable genetic backgrounds. This enables breeders to rapidly generate stable and uniform lines with specific genetic characteristics, facilitating the identification and fixation of beneficial mutations while eliminating deleterious ones. Reverse breeding holds immense promise for accelerating crop improvement efforts, offering a more efficient and predictable means of generating genetically uniform breeding populations. However, the successful implementation of reverse breeding relies on advanced molecular and computational tools to manipulate meiotic processes and identify target genomic regions accurately. Additionally, comprehensive evaluation of the resulting lines is essential to ensure the maintenance of desirable agronomic traits and the absence of unintended genetic alterations. Despite its technical challenges, reverse breeding represents a transformative approach in plant mutagenesis, poised to revolutionize crop breeding by enhancing efficiency, precision, and sustainability in the development of improved cultivars tailored to meet the evolving needs of agriculture and society.

4.4 Conclusion

The integration of advanced targeted mutagenesis breeding technologies into agricultural research holds tremendous promise for addressing the challenges caused by abiotic stresses in crop production. This precise manipulation of stress-responsive genes and associated molecular pathways offers powerful tool for the development of different crop varieties with increased tolerance to drought, salinity, cold, and heat. The simplicity, accessibility, and adaptability of CRISPR/Cas, coupled with its wide applicability, make it a revolutionary tool for sustainable crop improvement and enormous potential for developing climate-smart crops. Moreover, ZFN, TALENs, and ODM techniques further improve the efficiency and precision of crop breeding programs. These mutagenesis techniques revolutionized the editing of gene of interest. Therefore, it contributes to ensuring food security and sustainability amidst changing environmental conditions.

Acknowledgments The authors are grateful to Shoolini University, Solan, India, and Punjab Agricultural University, Ludhiana, India, for providing infrastructural support.

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Chapter 5

Implication of Molecular Techniques for Sustainable Crop Improvement



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5.1 Background

The field of plant breeding has undergone remarkable transformations, progressing from traditional methods to cutting-edge molecular breeding techniques. Conventional plant breeding follows the process of selecting superior plants that have been used for over 10,000 years but are insufficient for genome enhancement (Allwright & Taylor, 2016; Ahmar et al., 2020). Since the 1980s, the utilization of molecular markers for hybrid line selection has significantly enhanced breeding accuracy and efficiency. Plant breeders artificially breed desirable traits in diploid plants, like maize and tomatoes to accelerate the generation cycle in a year, unlike annual or perennial plants (Allwright & Taylor, 2016; Tieman et al., 2017; Ahmar et al., 2020). In this chapter we will delve into the techniques employed in molecular breeding, contrasting them to conventional breeding methods (Ahmar et al., 2020). The focus will be on understanding various molecular markers, MAS, the role of ZFNs, TALEN, and CRISPR-Cas9 in genome editing (Zhu et al., 2020; Gao, 2021), as well as the application of genome-wide associated studies (GWAS) in molecular breeding. Molecular markers are pivotal in identifying specific genes associated with desirable traits in crops, which are then used by MAS to select plants for breeding (Cobb et al., 2019). Genome editing, particularly CRISPR-Cas9, revolutionizes this process by allowing the modification of DNA, thus speeding up the development of crops with enhanced qualities. GWAS is another powerful tool that scans the genome of different plants of a species to find genetic variations associated with various traits. This comprehensive overview will enhance our understanding of how modern breeding methods can propel advanced crop improvement.

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Plant breeding and genome studies with modern molecular breeding technologies improve breeding accuracy and save time. The advent of *Agrobacterium*-mediated gene transfers in the early 1980s marked a significant milestone in plant biotechnology (Zhao et al., 2007). Transgenic research techniques have improved plant breeding precision considerably. However, first-generation GMOs could not predict transgene location, and it requires multiple transgenic events and tests to select plants that express desired traits (Fig. 5.1). By 1996, the successful integration of biotechnology through transgenic crops had become evident. This technique along with molecular markers has been instrumental in crop improvement. Continuous progress in plant biotechnology over the past 25 years has led to innovative tools for creating and analyzing genetic variation. In the last 15–20 years DNA sequencing methods have improved breeding precision and speed, leading to the development of “gene editing” or “genome editing” technologies, which are now widely used. The application of this technique to important cereals such as *Oryza sativa*, *Triticum aestivum*, and *Zea mays* and crops crucial for food security like potatoes (*Solanum tuberosum*) has been growing quickly (Chen et al., 2016; Zhu et al., 2020). Molecular breeding has gained significant information through extensive data on plant genes and genetic maps, leading to a new era of functional genomics. The successful genome sequencing of *Arabidopsis* and rice allows us to understand gene functions within their genome (Zhao et al., 2007; Jones et al., 2009). This progression reflects the continuous innovation in molecular breeding tools and precise crop improvement methods.

5.2 Plant Breeding Methods: Conventional Versus Modern Approach

The four primary methods of plant breeding include: (a) Conventional breeding: This method played a crucial role in the 1950s Green Revolution when scientists inserted the dwarf gene into wheat and rice, resulting in high-yield varieties (Ahmar et al., 2020; Yano et al., 2016; Hamdan et al., 2022). In this plants were crossed to combine improved and desirable traits (Fig. 5.1). However, for germplasm with low genetic variability, this approach was less effective; (b) Mutational breeding: In this method, crop plant genomes are randomly mutated and mutants with desirable traits are selected. However, it is laborious and time-consuming to identify mutants with desired traits from large populations of mutagenized plants (Raina et al., 2016); (c) Transgenic breeding (genetic modifications): In this method, foreign genes from different species are inserted into the plants to increase their disease resistance, nutrition content, etc. but, because of stringent government laws and ethical issues, their potential is restricted (Fig. 5.1; Chawla et al., 2023); (d) Genome editing: It is “next-generation plant breeding,” in which a targeted gene can be modified to produce desired features without introducing foreign DNA (Table 5.1). In conclusion,

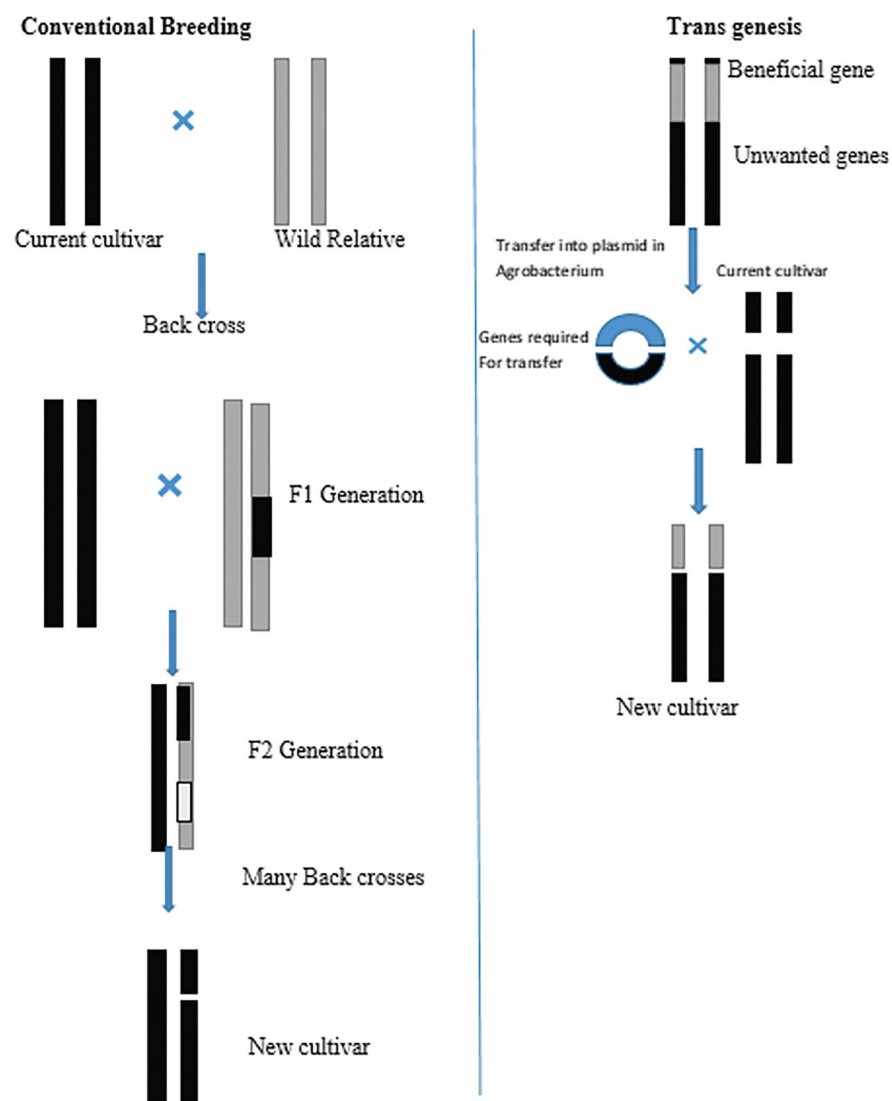


Fig. 5.1 Comparison between the conventional breeding method (Backcross) and modern molecular breeding method (Trans-genesis)

Table 5.1 List of basic plant breeding methods

Conventional plant Breeding	Mutational breeding	Transgenic breeding	Genome Breeding
Thousands of years	Since 1920s	1980s	2000s
Backcross breeding	Backcross breeding	Foreign DNA is inserted	8–10 years
Random, traits are selected from the parent's genome	Random mutagenesis	Traits introduced from other organism	Targeted mutagenesis
8–10 years	7–8 years	7–8 years	2–5 years
Not regulated	Not regulated	Regulated	Potentially regulated

all of these methods collectively contributed to crop improvement, assuring food security and sustainable agriculture over the years.

5.3 Molecular Markers

Genetic markers are specific DNA sequences located on chromosomes that help to identify specific traits in individuals, species, or populations without prior knowledge about the gene's function. They represent genetic variation within and between populations. While they are not the target genes themselves, they act as indicators that help locate these genes. Molecular markers have been pivotal in advancing modern agriculture by aiding in the production of crops that are climate-resilient, drought-tolerant, enhanced nutritious, and adapted to meet various needs (Yang et al., 2015). Their contribution to crop improvement and agricultural development is indeed significant. Molecular markers have several advantages such as they are highly specific and can be used to detect variation at the DNA level (Amiteye, 2021). Unlike some genetic tools like gene probes that require gene expression or phenotypic traits to be observed, molecular markers can identify genetic traits even if they are not expressed currently.

5.3.1 *Dominant Markers Versus Co-Dominant Markers*

Co-dominant markers are capable of detecting both dominant and recessive alleles in an individual allowing for the determination of whether an individual is homozygous or heterozygous (Xia et al., 2007). On the other hand, dominant markers can only reveal the presence of the dominant allele; thus, they do not provide information about the individual's exact genotype (Fig. 5.2). Some common types of molecular markers used in agriculture include (Table 5.2) the following:

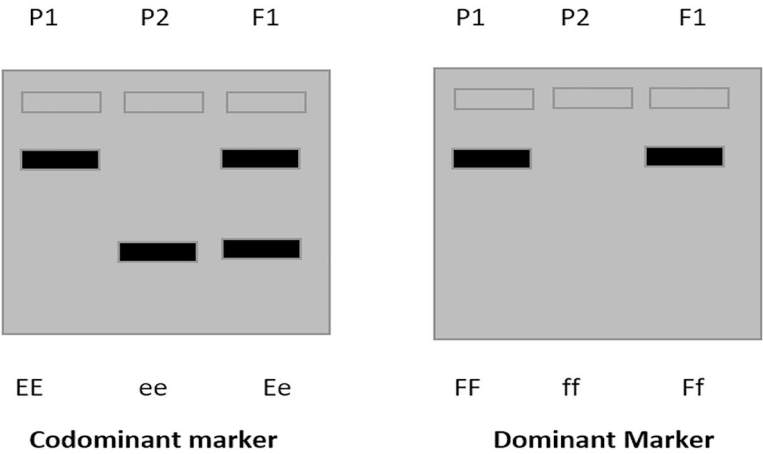


Fig. 5.2 Comparison of co-dominant and dominant markers

Table 5.2 Comparison of molecular markers used in plants

Markers	PCR based	Marker type	Polymorphism
RFLP	No	Co-dominant	Low-Medium
RAPD	Yes	Dominant	Medium-High
AFLP	Yes	Dominant	High
SSR	Yes	Co-dominant	High
SNP	Yes	Co-dominant	Very High
CAP	Yes	Co-dominant	High
ISSR	Yes	Dominant	High
STS	Yes	Co-dominant	High
SCAR	Yes	Co-dominant	High
SAMPL	Yes	Co-dominant	High
EST	Yes	Dominant	High
SRAP	Yes	Dominant	High
DArT	No	Dominant	High
SSCP	Yes	Co-dominant	High

- **Single Nucleotide Polymorphisms (SNPs):** It is variation at a single position in a DNA sequence, useful for high-resolution mapping. It is the most common type of genetic variation among individuals. In this low amount of DNA (0.02 µg) is required.
- **Simple Sequence Repeats (SSRs) (Microsatellites):** These are repeating DNA sequences of 2–5 base pairs, used for genetic diversity studies. In this low amount of DNA (0.02 µg) is required.
- **Amplified Fragment Length Polymorphisms (AFLPs):** Used to detect DNA polymorphism, helpful in constructing genetic maps. In this 0.5–1 µg of DNA is required.

- **Restriction Fragment Length Polymorphisms (RFLPs)**: They are differences in DNA sequences recognized by restriction enzymes, useful for mapping genes. In this 10 µg of DNA is required.
- **Random Amplified Polymorphic DNAs (RAPDs)**: Short random DNA sequences that amplify segments of DNA, used for genetic fingerprinting. In this low amount of DNA (0.02 µg) is required.
- **CAP (Cleaved Amplified Polymorphic Sequences)**: It differentiates plant varieties based on DNA sequence polymorphism detected by restriction enzymes.
- **S-SAP (Sequence-Specific Amplification Polymorphism)**: Combines the principles of AFLP with the specificity of retrotransposons-based markers.
- **ISSR (Inter-Simple Sequence Repeat)**: Amplifies regions between simple sequence repeats to reveal polymorphisms.
- **STS (Sequence Tagged Site)**: It is a short DNA sequence, usually 200–500 base pairs long, having a single occurrence in the whole genome, and can be used to identify specific genomic loci.
- **SCAR (Sequence Characterized Amplified Region)**: Derived from RAPD markers, they are specific DNA fragments that serve as reliable markers for genetic traits.
- **SAMPL (Selective Amplification of Microsatellite Polymorphism Loci)**: It targets microsatellite regions to detect polymorphisms.
- **EST (Expressed Sequence Tag)**: They are short stretches of sequence of complementary DNA that serve as a tag to identify gene transcripts.
- **SRAP (Sequence-Related Amplified Polymorphism)**: Targets open reading frames to identify functional genetic variations.
- **DArT (Diversity Arrays Technology)**: An array-based method for detecting genomic polymorphism without sequence information.
- **TRAP (Target Region Amplification Polymorphism)**: Combines fixed and arbitrary primers to amplify target regions, revealing polymorphisms.
- **SSCP (Single-Strand Conformation Polymorphism)**: Detects mutations by difference in electrophoretic mobility of single-stranded DNA.

All these markers—SNPs, SSRs, STSs, ESTs, etc.—are invaluable tools for plant breeding. They enable the selection and development of new crop varieties with desirable characteristics.

5.4 Marker-Assisted Selection (MAS)

MAS is the procedure in which markers are used for the selection of individuals in a population containing targeted genes or required characters for specified breeding objectives. MAS is useful in characters requiring progeny test, multiple character selection, and selection of recessive characters (Fig. 5.3). In progeny testing, MAS allows early selection of desirable traits, even before traits can be observed in offspring, thus saving resources that would otherwise be spent growing and progeny

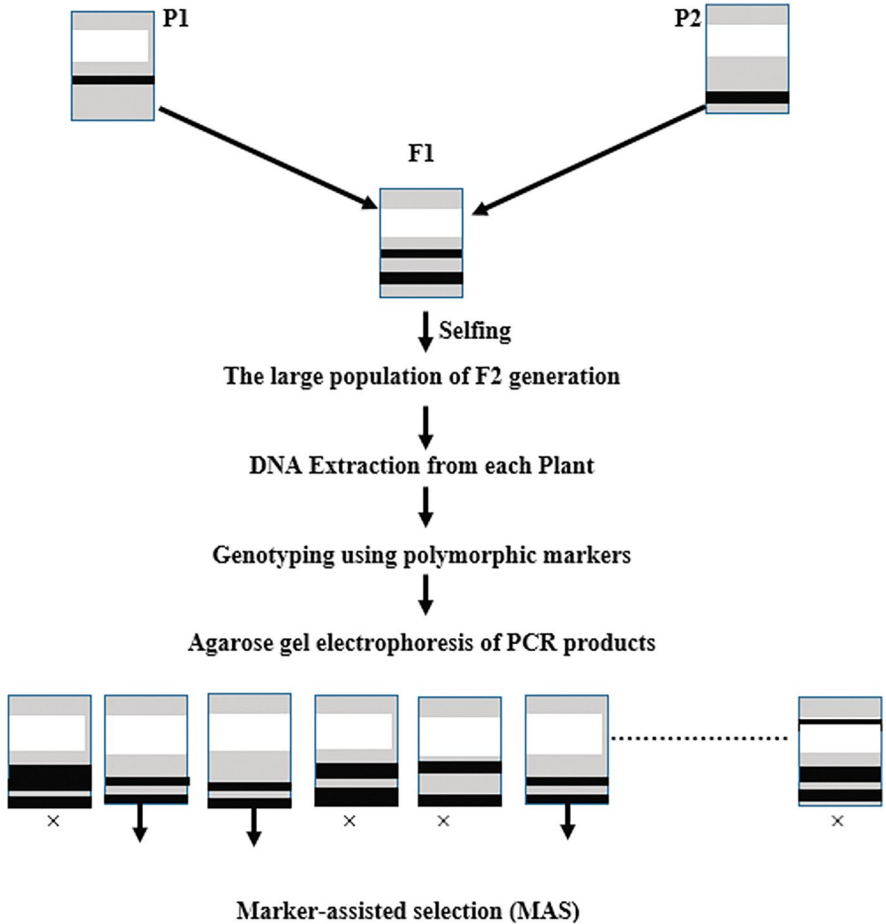


Fig. 5.3 Depiction of marker assisted selection in plants

testing (Cobb et al., 2019). For traits controlled by recessive alleles, MAS can identify carriers of these even if the traits are not phenotypically expressed, facilitating the breeding of plants (Nadeem et al., 2018) Overall, MAS is time, space, and resource-efficient in the selection of individuals in a population (Jiang, 2015). Some of the important methods used in MAS are:

5.4.1 Marker-Assisted Backcrossing (MABC)

It is a breeding technique used in plant breeding to transfer desirable traits from a donor parent into the recipient parent and retain its genetic makeup while incorporating the desired trait. Genetic markers are essential for tracking the presence of the

desired trait from the donor plant as it is backcrossed into the recipient plant over several generations. This technique is useful for transferring single genes or small gene clusters.

5.4.2 *Gene Pyramiding*

It is a plant breeding strategy that combines multiple genes/QTLs, conferring resistance to various diseases or pests, into a single cultivar. This method reduces chemical treatments and contributes to sustainable agriculture practices. MAS helps identify plants carrying desired genes at each breeding stage, ensuring all targeted genes are present in the final variety. It's crucial in gene pyramiding, combining multiple genes for enhanced traits or resistances (Rajput et al., 2023).

5.4.3 *Marker-Assisted Recurrent Selection (MARS)*

MARS is a method that uses MAS and recurrent selection to improve complex traits like yield or drought tolerance. This process involves selecting individuals from a breeding population, intercrossing, and repeating the process using markers. MARS enhances the F2 population through a cycle of MAS, incorporating phenotypic data and marker scores. This method can be performed without the need for pre-existing knowledge of (Quantitative trait loci) QTLs (Singh et al., 2021).

5.5 *Gene Editing*

It involves the modification, insertion, replacement, or deletion of DNA at a specific site in an organism's genome. This involves small-scale changes like point mutations or large alterations such as gene insertions or deletions resulting in desirable traits. Most advanced gene-edited crops exhibit simple mutations and do not contain transgenes. Targeted “genetic scissors” or “molecular scissors” such as CRISPR-Cas9 create double-stranded breaks at specific locations in the DNA sequence, which the cells then repair. Gene editing allows precise modifications, but these edits are hard to distinguish from natural variations or those produced by traditional breeding methods (Gao, 2021). CRISPR-Cas9 stands out as an efficient, fastest, cost-effective, and reliable “gene editing” tool. The typical process for genome editing includes:

- (a) **Nuclease Selection:** Choosing an enzyme capable of targeting and cutting the specific DNA sequence to be edited.

- (b) **Vector Construction:** Creating DNA molecules that deliver nuclease into the plant cells.
- (c) **Delivering Reagent:** Introducing the genome editing tools into plant cells.
- (d) **Plantlets Regeneration:** Using tissue culture technique to grow edited cells into small plants.
- (e) **Screening and Genotyping:** Testing the plants to ensure the genome has been successfully edited.

Gene editing can be performed through various methods including ZFNs and CRISPR/Cas system (Gao, 2021).

5.5.1 Zinc Finger Nucleases (ZFNs)

An older gene-editing tool that creates double-strand breaks at specific locations in the genome. They consist of Zinc finger proteins, which recognize DNA sequences in three base pairs, attached to the FokI restriction endonuclease. ZF is made up of three amino acids including Tyr6, Phe17, and Leu23 as well as seven conserved amino acids (Cys-Cys and His-His coupled via a zinc ion). Out of the two domains of ZFN FokI nuclease cleaves the DNA, and the zinc finger domains grant the specificity and recognize 18–24 bp of targeted DNA (Rasheed et al., 2021; Liu et al., 2022). ZFNs require dimerization of the FokI nuclease domain and a spacer sequence of 5–7 base pairs between binding sites for activity. Despite their specificity, ZFNs have limitations, such as potential off-target mutations and challenges in designing and selecting target sites due to the genome's vastness (Table 5.3).

Table 5.3 Comparison between different Gene editing tools

Features	Zinc finger nucleases (ZFNs)	TALEN	CRISPR-Cas9
Derived from organism	Derived from Eukaryotic gene regulator	Derived from the bacterium <i>Xanthomonas</i>	Derived from bacteria and archaea
Recognized Target DNA	18–24 bp	30–40 bp	22 bp + recognizes NGG, PAM sequence
Spacer Size	5–7 bp	14–16 bp	No spacer required
DNA recognition	DNA-Protein interaction,	DNA protein interaction	RNA-DNA interaction
Unit target reorganization	Zinc-finger Proteins(ZF motifs)	Pair of TALENs (via RVD tandem repeat)	17-20 bp sgRNAs
DNA cleavage and repair mechanism/ Endonuclease	Double-stranded break by FokI	Double-stranded break by FokI	Single or double-stranded break by Cas9
Efficiency	Low	Medium	High
Cloning	Essential	Essential	Non-Essential
Off-target Editing	High	Low	Moderate

5.5.2 *TALEN (Transcription Activator-Like Effector Nucleases)*

It is an older gene editing method discovered from bacteria of the genus *Xanthomonas*. They consist of 34 amino acids' DNA binding domains with repeat units that recognize specific DNA sequences, each determined by polymorphism repeated variable residues (RVDs). They are formed by FokI endonuclease and DNA binding domains. They require a spacer of 14–16 bp between the target site and FokI dimerization to function (Song et al., 2016; Rasheed et al., 2021). TALENs differ from ZFNs due to their one-to-one RVD-to-nucleotide binding ratio. Furthermore, TALENs are considered less cytotoxic, easier to design than ZFNs, with few off-target effects, but more expensive to engineer (Table 5.3).

5.5.3 *CRISPR-Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats)*

It is a revolutionary molecular breeding tool that allows genome editing of DNA segments. It consists of two main components: the Cas9 enzyme and a single guide RNA (sgRNA). The sgRNA is designed to be complementary to the target DNA sequence, directing Cas9 to make a double-stranded cut at the same genomic site. In the CRISPR-Cas9 system, Cas9 endonuclease works alongside two RNA molecules: trans-encoded CRISPR RNA (tracrRNA) and CRISPR RNA (crRNA). Cas9 enzymes operate as “Molecular scissors” cutting precisely in both DNA strands, allowing for the targeted modifications (Samanta et al., 2016; Zhu et al., 2020). The cell's repair mechanisms then fix the cut. This system has significantly advanced genome editing (Table 5.3). It involves specific binding to target DNA, precise DNA cuts, vector and sgRNA cloning, and delivery into plant explants (Arora & Narula, 2017). The CRISPR-Cas9 gene knockdown system includes several important components:

- (a) **Synthetic guide RNA:** It specifically binds to the target DNA sequence for editing.
- (b) **Cas9 cleavage:** Cas9 enzyme performs precise cuts in the DNA, typically downstream of the PAM (protospacer adjacent motif) sequence, which guides Cas9 to the correct genomic site (Ahmar et al., 2020).
- (c) **Vector and sgRNA cloning:** Select a binary vector to clone the snRNA.
- (d) **Transformation:** The CRISPR/Cas9 construct is delivered to plant explants via *Agrobacterium*-mediated transformation or microprojectile gene bombardment.

CRISPR-Cas9 has become the preferred method for plant genome editing due to its affordability, ease of use, precision, efficiency, and faster method compared to older techniques like ZFNs and TALENs. CRISPR-Cas9 can target and edit DNA

regions that are methylated, which is limited for older techniques. Its advantages are particularly beneficial in crop improvement, where it has been used to enhance resistance to pests, drought, and crop yield. Examples of its application include creating rice varieties with better drought and salinity tolerance, tomatoes with extended shelf life, and wheat with lower gluten content for gluten sensitivity (Yano et al., 2016; Tieman et al., 2017). This makes it a valuable tool for advancing agricultural research and development.

5.6 GWAS (Genome-Wide Association Study)

It is a powerful method for examining the genetic makeup of complex (Wang et al., 2014). Abiotic stress tolerance, biotic disease resistance, and a range of agronomic measures have all shown the significance of GWAS in plant science since high-density SNP arrays and next-generation sequencing technology became available. The fundamental aim of GWAS is to find relationships between genotype or allele frequency and trait status as expressed in phenotypic observations. The starting point is to assess characteristics and choose an acceptable study group based on size and genetic and phenotypic diversity. Choosing a novel or well-studied population will determine whether or not genotyping is required. One way to achieve is whole-genome sequencing or single nucleotide polymorphism (SNP) arrays and imputations. Then, using meta-analysis to increase the statistical power to uncover relationships, genomic areas that have a genome-wide association considering the variation of the desired phenotype are identified through association tests.

It has been successful in identifying the genetic basis for variation in a wide range of complex phenotypes over the past 15 years, including physiological and agronomic features in plants (Chen et al., 2016; Tieman et al., 2017; Tian et al., 2020). Illusory relationships and, hence, erroneous discoveries might result from unbalanced relatedness and population structure between individuals. To solve this issue, an enormous amount of work has been done to statistically account for population structure (Devlin & Roeder, 1999; Liu et al., 2016). For example, in mix linear models (MLM), population stratification is fitted as a fixed effect, whereas kinship between individuals is integrated through the variance-covariance structure of the random effect for every individual (Yu et al., 2006; Zhao et al., 2007). This technique, known as “phenotype first,” screens the unrelated population first to see if the phenotype is present or absent. It also entails quickly screening a heterogeneous population’s whole genome to identify the greatest number of genetic variants linked to a given trait. Linkage research depends on the gene and marker co-segregating, whereas GWAS takes advantage of the straightforward relationship between a polymorphism (SNP) and the desired trait. It is recommended that the population size be quite big to validate the link between the SNP and the desired characteristic. Linkage disequilibrium (LD) analysis, which shows the absence of recombination between nearby SNPs, is another name for GWAS.

Although SNP-based GWAS is also widely used, it has drawbacks such as weak signals building up among related SNP sets and frequently disregarded relationships between SNPs within a gene (Fang & Luo, 2019). Haplotype- and gene-based GWAS have been developed to overcome these difficulties. Although they are less effective than SNP-based GWAS at detecting QTL, particularly for rare alleles, they are highly effective at detecting responsible haplotypes and can provide new possibilities for complicated traits (Yano et al., 2016; Zhang et al., 2016).

The concept of each of these tactics is the idea that significant effects and phenotypes follow a normal distribution. There are still two further significant developments to discuss. A supplementary method for mild effect loci, infrequent variations, and aberrant phenotypic distributions is the Anderson Darling test. Additionally, fine mapping based on statistical techniques have been provided by (Schaid et al., 2018). Understanding that concerned loci typically have minimal effect size and just partially explain heredity considerably subdued the initial hype surrounding GWAS. That being said, there is very little missing heritability when large and diverse populations are included. There is a definite relationship between the population's size and SNP count, as evidenced by real data suggesting that the rate of locus discovery in GWAS accelerates beyond a certain sample size. As mentioned earlier, there are several methods for genotyping genetic variants, the most popular being whole-genome sequencing and SNP arrays. The latter is becoming prevalent due to the declining costs associated with sequencing. SNP arrays offer great accuracy and a well-established analysis pipeline in addition to their lower cost. While the cost and accuracy of whole-genome sequencing is higher but can detect rare and extremely rare changes if there is sufficient sample size. Additionally, whole-genome sequencing makes fine mapping simpler; nevertheless, these advantages come at the cost of increased computational burden and multiple testing (Tam et al., 2019).

5.6.1 Present Scenario and Approaches of GWAS

Biology relies on understanding complex traits' genetic architecture, impacting agriculture and evolution. Research on association mapping was started using model plant and agricultural species, due to genomic technology advancements and trait variation across genetic backgrounds. GWAS gathers phenotypic and genotypic data for large populations (Zhu Guang Tao et al., 2018). Genotype data is derived from single nucleotide polymorphisms (SNPs) discovered through re-sequencing, or genotyping based on arrays. Statistical techniques are utilized to identify genetic markers associated with a trait. Gametic-phase disequilibrium (LD) is the basis of GWAS, where the desired attribute may be linked to SNPs at the causative locus with high LD. Apart from the fact that linkage analysis was the primary tool to study the intricate traits, association studies were acknowledged for their potential benefits. Compared to linkage analysis, association mapping has the advantage of

avoiding experimental crosses, increasing the ability to use smaller LD blocks to increase resolution and identify genes with lesser impact sizes (Fig. 5.4).

5.6.2 Factors Influencing GWAS

Phenotypic variation: The most common method to determine the number of outliers in phenotypic data and whether they are effective or not is to make use of a boxplot that makes it simple for data visualization and extreme outliers ought to be removed. In the meanwhile, eliminating outliers should not have a major

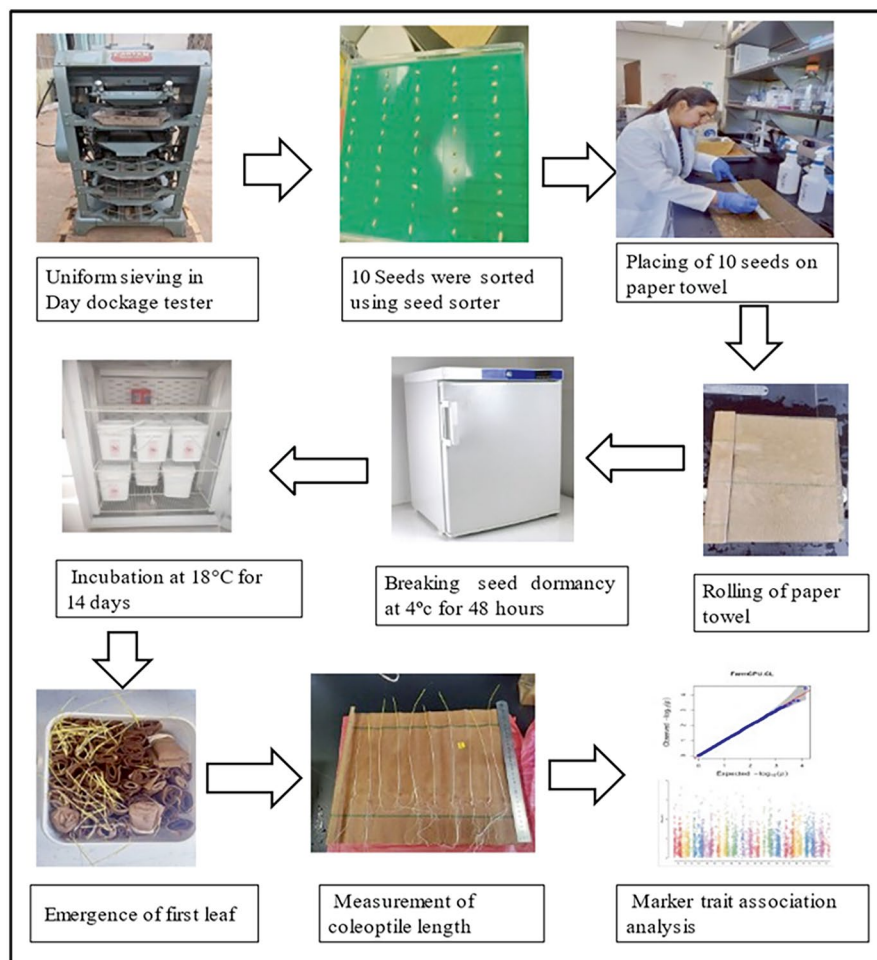


Fig. 5.4 Brief methodology of GWAS analysis for measuring coleoptile length in hard winter wheat (unpublished results)

effect on phenotypic variation because it plays a key role in the association analysis. Furthermore, as heritability is a significant predictor of how much genetic variance contributes to the phenotype and how much the phenotype is connected to the genotype, GWAS only analyzes features with moderate to high heritability estimates (Alqudah et al., 2020).

Population size: In order to obtain meaningful results, population size is important. Since population size is essential for defining portions of phenotypic and genotypic diversity, larger populations have a bigger effect and can tolerate higher frequencies within the population. Consequently, a small sample size is a drawback that reduces the power of GWAS. A sample size of 100–500 is appropriate for GWAS (Kumar et al., 2012).

Population structure: It is a statistical method for assessing relatedness correlation between people within a population, which must be carefully handled throughout studies and result in interpretations because of admixture and historical structure. When selecting a population for association analysis, scientists establish the framework—based on factors like growth patterns or geography—those results in a certain genetic variation and has an impact on how association analysis is ultimately used. This is a basic flaw in the GWAS study as not every person is genetically quite distinct from the others.

Linkage disequilibrium: A key component in figuring out how many markers are required for whole genome scanning is LD, a statistic that quantifies the division between loci (Myles et al., 2009).

5.6.3 Software for GWAS

PLINK: It makes it possible to examine a large genotypic and phenotypic dataset. It is accessible at <http://zzz.bwh.harvard.edu/plink/>. PLINK offers basic association tests, meta-analyses, population stratification analysis, and supplementary tests like gene-based association testing and epistasis screening. Graphical representations can be used for the Manhattan plot, Q-Q plot, and multidimensional scaling (for population structure). Additionally, PLINK has the ability to generate tables with GWAS and LD results for SNP markers.

TASSEL: The most widely used software in plants is TASSEL (Trait Analysis by Association, Evolution, and Linkage). TASSEL includes two advanced statistical methods for doing GWAS, called GLM and MLM. TASSEL may use PCA and kinship analysis to analyze population structure. LD is also included in TASSEL (Bradbury et al., 2007).

GenStat: A statistical program called GenStat for Windows OS uses bi- and multiallelic markers to evaluate marker-trait correlation in a genetically diverse population. GWAS can be performed with GenStat using the GLM or MLM models, and genetic relatedness can be managed with Kinship or PCA for population structure analysis.

Table 5.4 Comparison of Traits improved through GWAS

Crop	Scientific name	Chromosome number	Genome size	Improved trait
Hexaploid wheat	<i>Triticum aestivum</i>	$2n = 6x = 42$	~17Gb	Drought and heat stress
Tetraploid wheat	<i>Triticum turgidum</i>	$2n = 4x = 28$	~12Gb	Fusarium head blight resistance
Rice	<i>Oryza sativa</i>	$2n = 24$	~ 420 Mb	Root morphology traits
Maize	<i>Zea mays</i>	$2n = 20$	~ 2.4 Gb	Early maturity and other agronomic traits
Barley	<i>Hordeum vulgare</i>	$2n = 2x = 14$	~ 5.3 Gb	Grain yield and other agronomic traits
Sorghum	<i>Sorghum bicolor</i>	$2n = 20$	~730 Mb	Inflorescence architecture

RStudio: Recent developments in the free software R statistical environment have made GWAS tools widely available (Storey & Tibshirani, 2003).

5.6.4 Applications in Crop Improvement

The GWAS data can be used for many purposes, such as gene editing, breeding, genetic mapping, and search for candidate genes. High-throughput phenotyping systems or incredibly precise phenotyping by researchers will additionally boost GWAS's power in identifying new loci. These discoveries provide fresh opportunities for crop breeding, the genetic and genomic analysis of important agronomic traits, and other field traits (Table 5.4). Genome-wide association studies have examined agriculturally significant characteristics for a wide range of major crop species, including barley (*Hordeum vulgare* L.), cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], rice (*Oryza sativa* L.), maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and many other species beyond the model plant species *Arabidopsis* (Zhao et al., 2007; Sukumaran & Yu, 2014; Yano et al., 2016).

5.7 Conclusions

Plant breeding techniques have improved over the last 30 years, with the transfer from molecular markers to genome editing tools. Despite advances, obstacles persist, such as the requirement for precise phenotyping and the development of efficient markers for underutilized crops. While CRISPR technology has transformed plant breeding and genetics by allowing genome editing across commercially significant plants, some marker-assisted selection (MAS) methods continue to require comprehensive genome knowledge, resulting in time-consuming lab effort.

Furthermore, it has also identified thousands of loci linked to different quality and quantity parameters in crop species and various ways for increasing power and processing speed. It is important to consider the synergistic interaction between genome editing and GWAS. To successfully modify a genome, one must first identify the SNPs and then investigate which gene's corresponding protein is in charge of them, arguing that GWAS analysis is the foundation of effective genome editing. In the coming years, plant breeding will take an integrated approach that incorporates all currently available approaches.

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Chapter 6

Mapping Genes and Approaches for Climate-Resilient Agriculture in Agricultural Crops



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6.1 Background

Climate change pertains to significant and persistent modifications in the expected patterns of customary weather in a specific region or the entire globe over an extended period. This refers to abnormal departures from the usual climate patterns and the consequences of these variations on various regions of the Earth (Verma et al., 2023). These alterations may take several decades, centuries, or even millions of years. Nevertheless, the increase in human activities such as industrialization, urbanization, deforestation, agriculture, and alterations in land use patterns lead to the emission of greenhouse gases. As a result, the pace of climate change increases. Climate change scenarios involve higher temperatures, changes in rainfall patterns, and higher levels of atmospheric CO₂. The increasing effects of climate change pose substantial challenges to global agricultural systems. The worldwide disturbance of conventional agricultural methods and harvest productivity is attributed to escalating temperatures, shifting precipitation patterns, and a surge in the occurrence of severe weather phenomena.

To meet the food and nutritional needs of the population by 2050, there needs to be a 60% increase in global agricultural production from 2005/2007 to 2050. This increase should be divided between a 77% rise in developing nations and a 24% rise in wealthy countries. Climate change harms agricultural production and is expected to decrease world maize and wheat production by 3.8% and 5.5%, respectively,

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according to Lobell et al. (2011). Plants encounter several abiotic challenges, including salinity, drought, heat stress, cold stress, etc., due to climate variables. The major adverse effects of climate change are water scarcity, depletion of soil fertility, and agricultural damage caused by pests (Baul & McDonald, 2015).

The implications stated above emphasize the urgent need for innovative strategies to strengthen the resilience of agricultural systems. Traditional agricultural methods are unable to cope with rapid changes, so it is necessary to shift towards more sustainable and adaptive ways.

The sustainability of agricultural production is strongly dependent on the development and implementation of novel approaches. Novel technologies and techniques have recently evolved in the agri-food industry, with a specific focus on climate-smart solutions. These solutions aim to not only reduce the impact of climate change but also improve the financial situation of producers (Zougmore et al., 2021). These technological innovations enhance the efficiency of resource utilization, boost productivity, and enhance the ability of agricultural systems to withstand and recover from challenges. These technologies enable producers to make well-informed decisions, streamline procedures, and get access to equitable market opportunities (Karunathilake et al., 2023).

Genetic mapping is a potent technique for bolstering the resilience of crops against the effects of climate change. Genetic mapping entails the identification and characterization of particular genes and genomic areas that are linked to advantageous qualities, such as the ability to withstand drought, tolerate high temperatures, and possess immunity to diseases. In order to expedite the progress of crop varieties that can adjust to climate change, scientists must comprehend the genetic foundation of these characteristics and employ focused breeding or genetic engineering techniques.

The advancements in omics technology have greatly transformed our efforts to improve crops. These technologies have strengthened the tools available to crop breeders and have energized breeding programs that utilize omics techniques to enhance various agronomic traits (Li & Yan, 2020). Omics technology represents a cutting-edge molecular approach that delves into the intricate genomic functions within organisms. This innovative methodology encompasses DNA sequencing and the profiling of expressed transcripts and translated proteins, providing a comprehensive view of biological processes (Missanga et al., 2021). The term “omics” originates from the Greek “-ome,” denoting “whole,” and pertains to scientific disciplines that explore various categories of biological molecules constituting entire biological systems (SETAC, 2019). By integrating genomic mapping with other omics technologies, such as transcriptomics and metabolomics, we can acquire a comprehensive comprehension of the molecular pathways that govern stress responses in crops. This comprehensive approach not only enables the identification of essential genes but also uncovers the complex gene networks and mechanisms that contribute to climate resilience.

6.2 Genetic Foundations of Climate Resilience

The urgent requirement to ensure global food security in the coming decade is being driven by climate change and rapid population increase. This necessitates the development of future crops that possess high resilience and adaptability to changing conditions. The extensive process of domestication has resulted in cultivated crops having genetic disadvantages, which raises worries about their ability to adapt to new challenges and limits their value in breeding programs. To enhance crop improvement in the future, it is necessary to combine different genomic techniques, such as high-throughput sequencing and machine learning. This will allow us to utilize the diversity of germplasm and overcome challenges caused by domestication, complex traits, laborious breeding processes, expansive multidimensional phenotypes, and large amounts of data (Saad et al., 2022).

To advance climate-resilient agriculture, it is essential to examine the genetic factors that contribute to the resilience of crops. Genetic mapping and related techniques offer powerful tools for understanding the complexities of plant genomes and identifying the genetic variations that contribute to important traits necessary for adapting to different climates. By gaining a basic understanding of these genetic components, scientists can concentrate on specific regions of the genome that are associated with resistance to climate conditions. This will facilitate the advancement of precise breeding methodologies and biotechnology treatments.

6.2.1 *Complex Genetic Network Regulating Abiotic Stresses*

The growing incidence of severe weather events, along with alarming predictions of climate change, highlights the urgent need to enhance the ability of crops to withstand environmental (abiotic) and pathogen (biotic) stress. This is crucial for ensuring food security for a rapidly expanding global population (Bailey-Serres et al., 2019).

Climate change-induced abiotic factors that disrupt crop productivity include inundation, aridity, soil salinization, and severe temperatures. The enhancement of crops' resilience has been achieved by activating methods that involve the identification of genes related to crucial characteristics and signal transduction pathways, which are then followed by breeding or engineering processes. Achieving resilience without compromising overall yield is a significant problem (Mickelbart et al., 2015).

6.2.2 Temperature

The physiological processes of plants and the amount of crops produced are significantly influenced by temperature stress. This stress gets worse with climate change, resulting in more frequent and severe fluctuations in temperature. Researchers have analyzed the genetic and molecular responses to temperature stresses, revealing intricate mechanisms that elucidate how plants adapt to and withstand these environments. The primary characteristic of climate change is the variability of temperature. Multiple authors have researched the genetic and molecular factors associated with plants' ability to respond to temperature-induced stressors. Exposure to temperature stress can result in significant harm to the cell membrane and protein structure, which in turn leads to the generation of reactive oxygen species (ROS) and the initiation of oxidative stress. It also led to a drop in the production of plant hormones and antioxidants, as well as changes in the arrangement of cellular structures, ultimately causing disruptions in hormonal balance.

Table 6.1 provides a concise overview of important studies on the genetic mechanisms that underlie plant stress responses, specifically about heat and cold tolerance. These studies focus on identifying genes and understanding the regulatory

Table 6.1 Key genes for heat and cold tolerance

Identified gene/protein	Research focus	Role in stress tolerance	Reference
OsBHT	QTL mapping for rice heat tolerance during booting phase	Enhancing heat tolerance in rice	Park et al. (2020)
FaG6PDH-CY	Investigation of cold tolerance in strawberries	Enhancing cold tolerance by reducing ROS accumulation	Zhang et al. (2020)
TaPIN	Study on PIN gene family in common wheat	Role in developmental processes and stress responses	Kumar et al. (2021)
ICE-CBF-COR pathway	Impact of low temperature stress on plant growth and development	Activation of osmoregulation genes under low temperature	Theocharis et al. (2012)
ICE	Regulation of osmoregulation genes under low temperature stress	Key regulator of cold acclimatization	Zhang et al. (2011)
ICE	Role of ICE transcription factor in cold acclimatization	Regulates cold acclimatization through downstream genes	Ritonga and Chen (2020)
TaNAC2L	Activation of heat-related genes by TaNAC2L in Arabidopsis	Enhances heat tolerance by controlling stress-related genes	Guo et al. (2015)
SIJA2	Impact of NAC transcription factor on heat stress vulnerability	Decreases SA accumulation, making plants more susceptible	Liu et al. (2017)

pathways involved. The results emphasize possible areas for improving stress resistance in crop species to alleviate the effects of climate change.

6.2.3 Drought

Gaining insight into the molecular pathways that drive plant responses to drought stress is essential for the development of crops that can withstand climate challenges. In this study, we explore the crucial genes and regulatory mechanisms that play a role in the response to and adaptation of plants to drought conditions, across different plant species.

According to González-Villagra et al. (2017), ABA enhances the activity of genes involved in anthocyanin synthesis by controlling the microRNA156 during periods of drought stress. Wheat frequently experiences drought, which is a prevalent environmental stressor. Under drought stress, the majority of the genes responsible for anthocyanin production in purple wheat GZ1 were found to be downregulated.

ABA synthesis relies on 9-cis-epoxy carotenoid dioxygenase (NCED). The NCED gene controls *Arabidopsis thaliana* drought tolerance. *Arabidopsis* overexpressing the AtNCED3 gene increases endogenous ABA, and dryness and ABA enhance gene transcription. Plants with this gene upregulated had lower leaf respiration and higher drought tolerance (Yang et al., 2021).

According to Li et al. (2018), the overexpression of OsERF71 in upland rice resulted in increased drought resistance. This was achieved by upregulating the expression of OsP5CS1 and OsP5CS2, which are responsible for regulating proline synthesis. It is worth noting that this effect was shown in lines that overexpressed OsERF71, and not in lines where OsERF71 was interfered with.

Agarwal et al. (2016) investigated the AP2/ERF and HSP90 gene families across chickpeas, pigeon peas, and common beans under diverse biotic and abiotic stresses. Their study explored the response of these gene families to varying environmental challenges. In a separate study, Wang et al. (2018) demonstrated the drought, salinity, and temperature stress resistance conferred by the maize WRKY transcription factor (ZmWRKY4) in transgenic *Arabidopsis* plants. ZmWRKY4 not only upregulates stress-tolerant genes but also enhances the activity of essential stress-related enzymes like peroxide dismutase and catalase, thus improving drought resilience. Similarly, He et al. (2016) showed that the wheat transcription factor TaWRKY33 enhances drought and salt stress tolerance in genetically modified *Arabidopsis* plants, illustrating its potential as a valuable genetic resource for improving crop resilience under adverse environmental conditions.

The results emphasize the capacity of genetic engineering and manipulation of transcription factors to improve the ability of plants to withstand drought stress. This progress opens up opportunities for creating crop types that can adapt to changing climate conditions, which is crucial for sustainable agriculture.

6.2.4 Salinity

The presence of high salinity levels presents considerable obstacles to the growth and productivity of plants. Therefore, it is necessary to investigate transcription factors (TFs) that can enhance the ability of crops to tolerate salt. The primary transcription factors (TFs) were associated with salinity stress and found to have significant promise in enhancing crop tolerance to salt stress. According to Hussain et al. (2021), they demonstrated that increasing the activity of the ThNAC12 transcription factor improved the ability of *Tamarix hispida* plants to tolerate high salt levels. This was achieved by regulating the removal of reactive oxygen species (ROS) by direct control of the expression of ThPIP2;5. This finding was also supported by Hussain et al. (2021). According to Zhu et al. (2015), the MYB-type transcription factors (TFs) in rice, specifically OsMYB91, have been found to exhibit overexpression, leading to improved salt tolerance. This overexpression also results in a greater ability to remove reactive oxygen species (ROS) and higher amounts of proline in rice.

Specifically, the MADS-box type transcription factors (TFs), specifically OsMADS25, have been discovered to demonstrate overexpression, which has led to an improvement in rice's ability to tolerate salt. According to the findings of a study that was carried out by Xu et al. (2018), this overexpression results in increased levels of free proline content and decreased levels of metastatic ductal accumulation. Furthermore, the moderate expression of OsPIP1;1 in rice was observed to result in higher salt tolerance and water conductivity, according to the findings of the research carried out by Liu et al. (2013). These studies highlight the potential of manipulating transcription factors to improve plant resistance to salt stress. This offers intriguing opportunities for generating crop types that can tolerate high salt levels, which is essential for sustainable agriculture in saline areas.

6.2.5 Flooding

The genetic basis of plants' ability to withstand and adapt to flooding, specifically climate resilience, is defined by crucial biochemical processes and genetic adjustments. In wheat roots, the application of an ethylene precursor before treatment increased the expression of three RBOH genes, which are responsible for generating reactive oxygen species (ROS). This also stimulated the development of lysigenous aerenchyma, a type of tissue that helps with oxygen transport, in conditions where water is stagnant. This mechanism may be one of how wheat seedlings adapt to hypoxia stress (Yamauchi et al., 2014). Kuroha et al. (2018) discovered a scarce variant of the SD1 gene (SEMIDWARF1) involved in the production of gibberellin. This variant enables plants to adapt to deep water conditions. The SD1 protein stimulates the production of gibberellin, namely GA4, which leads to the elongation of internodes.

Biotechnology enables speedier modification of crops compared to traditional methods, hence expediting the implementation of policies to address rapid and severe climate change. The cultivation of resistant and biotech-resistant crops has been rapidly increasing to manage the proliferation of pests and illnesses, which are emerging due to climate change. Utilizing resistant cultivars decreases the need for pesticide usage, resulting in a reduction of CO₂ emissions. Researchers have created new types of crops that are specifically designed to withstand the many nonliving factors caused by climate change (Aslam et al., 2020). The utilization of current biotechnology in the creation of drought-tolerant crops has the potential to enhance global food security. Drought-tolerant crops play a crucial role in maintaining plant growth and productivity, as well as expanding the amount of arable land available worldwide.

The progress made in comprehending the genetic foundation of flood tolerance creates opportunities for pioneering biotechnological methods to cultivate climate-resilient crops, which are essential for guaranteeing food security and agricultural sustainability in the face of fast climate change. Comprehending the interaction and combined impacts of these genes is crucial for devising comprehensive strategies to improve the ability of crops to withstand climate challenges. Furthermore, the investigation of gene-environment interactions offers a valuable understanding of how genetic adaptations can be precisely adjusted to enhance crop production under different climatic conditions.

6.3 Significance in Mitigating Climate Change Effects on Crops

The importance of characteristics such as drought tolerance, heat resistance, and adaptability is extremely significant when it comes to reducing the effects of climate change on crops. These characteristics empower plants to flourish in adverse conditions, reducing the amount of crop loss and preserving agricultural output despite fluctuations in climate. Research suggests that genetic enhancement in drought tolerance has the potential to reduce around 25% of losses caused by drought (Edmeades, 2008). Through the utilization of climate-resilient crop varieties that possess improved genetic features, farmers can decrease their dependence on agrochemical inputs, preserve water resources, and establish more sustainable farming systems.

6.4 Advanced Genomic Technologies in Gene Mapping

The progress of omics technology, databases, and genome editing tools has simplified the investigation of the genetic elements that contribute to the adaptability of wild populations to climate-related challenges. The objective of this research is to alleviate the detrimental impacts of climate change and cultivate crops that are more suitable for evolving climatic circumstances (Sork, 2018). The strategies include QTL mapping, genome-wide association studies (GWAS), landscape genomics, transcriptomics, metabolomics, and other techniques.

6.4.1 GWAS

GWAS is an effective approach for identifying genes linked to complex features, such as those related to the ability of crops to withstand climate challenges. GWAS utilizes the inherent genetic differences seen in distinct germplasm collections to find genetic markers that are associated with specific phenotypic features. GWAS allows for the discovery of genomic areas that include genes responsible for variations in traits. This is done by examining large-scale databases of genotype-phenotype information from different populations (Li et al., 2014).

GWAS is a widely recognized method in the field of agriculture. It is effective in identifying and understanding the connections between complex diseases and common genetic variations. However, the challenge of missing heritability remains a significant obstacle. To overcome this challenge and identify a wide range of QTLs, it is necessary to have access to millions of molecular markers and a large number of individuals. The GWAS is a powerful method for identifying genes that contribute to various traits in plants. It achieves this by examining the relationship between single nucleotide polymorphisms and specific characteristics of interest. This information can then be utilized to precisely locate these associations. GWAS examines the entire genome to identify any potential correlation between phenotypes and markers spread across the entire genome. In whole-genome scans, markers that are evenly spread throughout the entire genome are used to assess all genes at the same time.

Conventional linkage mapping, also known as QTL mapping, is frequently employed to identify specific genomic areas (QTL) that control desired attributes. The family-based mapping analysis relies on the occurrence of genetic recombination and segregation in the offspring of two parents during the creation of mapping populations. These factors have an impact on the precision of genetic mapping and the diversity of alleles present (Li & Yan, 2020). Generating a mapping population consisting of bi-parental homozygous lines for QTL mapping in tree crops is a highly time-consuming, labor-intensive, and complex process. GWAS offers more detailed maps by taking into account the historical recombination through linkage disequilibrium among the representative accessions in the association mapping

populations. This leads to an improved resolution for association analysis because of the rapid decline of linkage disequilibrium (LD) (Xiao et al., 2017). To easily discover the QTLs, the presence of many alleles for a certain trait is taken into account in GWAS due to the extensive collection of germplasm lines (Ashwath et al., 2023).

6.4.2 Design and Development of GWAS

To execute a good GWAS experiment, it is essential to follow three crucial steps: phenotyping, genotyping, and performing GWAS analysis (Ashwath et al., 2023).

Phenotyping is the process of analyzing a plant's morphological, physiological, and biochemical aspects to understand its structure, composition, and growth (Paez-Garcia et al., 2015). Phenotyping can be performed repeatedly in several locations and/or time periods to obtain a thorough comprehension of the influence of minor alleles and determine the most significant phenotypes. Genotyping is the process of using molecular markers to identify the genotypes of a certain set of chosen genotypes that are also used for phenotyping. Co-dominant markers, such as simple sequence repeat (SSR), have been used in association mapping studies in several crop plants (Rasool et al., 2022).

6.4.3 Genome-Wide Association Study (GWAS) Analysis and Platforms

The general linear model (GLM) and the mixed linear model (MLM) are often employed as statistical models for conducting genome-wide association studies (GWAS) analysis (De La Torre et al., 2022). Generalized linear models (GLMs) utilize the population structure, as well as phenotypic and genotype data, to establish marker-trait relationships. Before doing GWAS analysis, it is necessary to clarify the subpopulations within the genotypes to prevent spurious relationships. The population structures are characterized based on familial relatedness, which encompasses linkage disequilibrium and kinship. Software tools like STRUCTURE and GAPIT are utilized to analyze population structure and familial relatedness, respectively, to prevent spurious connections (Xiao et al., 2021). TASSEL has a variety of data visualization tools that display data in the form of scatter plots for principal component analysis (PCA), linkage disequilibrium (LD), Manhattan plots, heat maps, phylogenetic trees, and phenotypic variation explained by markers. PLINK is a software tool used for conducting whole-genome association studies. It can analyze large groups of individuals simultaneously by detecting stratification, performing basic association tests, conducting meta-analyses, and running additional tests like gene-based association testing and epistasis screening. PLINK also provides

visual representations of the results, including Manhattan plots, Q-Q plots, and multidimensional scaling (Choi et al., 2020). The application of GWAS has proven to be highly effective in elucidating the connections between molecular markers and phenotypes. However, the presence of uncommon variants and the intrinsic population structure in natural populations can diminish the statistical strength of these relationships (Xiao et al., 2017).

6.4.4 Molecular Markers

The use of DNA markers is a highly effective method in genomic technologies for mapping genes and enhancing the genetic makeup of plants. It allows for accurate genetic identification, assessment of variations, and the creation of genetic linkage groups with great precision. DNA markers are highly versatile tools for enhancing a plant's genetic composition. They can be employed to determine the genetic origins of parent plants, evaluate genetic diversity, and precisely identify, validate, and establish genetic linkage groups. Various molecular markers are commonly used in research, including techniques such as restriction fragment length polymorphism, random-amplified polymorphic DNA, amplified fragment length polymorphism, microsatellites, and single nucleotide polymorphisms. The DNA markers linked to the QTL area were utilized to accelerate and precisely carry out choices, as well as to add advantageous characteristics in numerous crop species (Varshney, 2016).

Microsatellite markers, also known as simple sequence repeat markers, are appropriate for gene mapping due to their proven effectiveness in assessing genetic variations in various crop species. Their capacity to be replicated, straightforward procedure, and notable capability to identify genetic variations and co-dominant traits make them the preferred method for analyzing DNA profiles of plant germplasm. These markers enable the assessment of offspring characteristics, the study of evolutionary processes, and the identification of genetic information and variation through progeny evaluation, evolutionary research, and genome mapping (Younis et al., 2020).

A study was undertaken in wheat to assess the genetic diversity of salt-tolerant genotypes. The study utilized plants that were cultivated in a field influenced by salinity. The DNA markers successfully distinguished between genotypes that are resistant to salt and those that are vulnerable to salt. Genetic variation was confirmed by the use of polymorphic primer matching between tolerant and sensitive genotypes. Genetic information can be used to generate wheat varieties that are resistant to salt by crossing genotypes that are resistant and susceptible to salt (Bhutta & Amjad, 2015).

By strategically utilizing DNA markers, scientists can accurately chart genes of significance, evaluate genetic variation, and expedite the creation of crop varieties that are resistant to salt. This highlights the crucial role of molecular markers in advancing genomic technologies for enhancing crops and adapting them to stressful conditions.

6.5 High-Throughput Sequencing

High-throughput sequencing, or Next-Generation Sequencing (NGS), has transformed genomics by allowing fast and cost-efficient examination of DNA sequences on a massive scale. This technology is crucial in revealing the intricacies of plant genomes, especially in the context of discovering genes linked to climate resistance in crops. The forward genetic approaches based on NGS have adhered to three primary methods, which are concisely outlined below.

6.5.1 *Genotyping by Sequencing (GBS) Approach*

GBS is a method utilized for the identification and analysis of a vast number of SNPs throughout an entire genome. GBS is a method that employs restriction enzymes to simplify the complexity of the genome. GBS is a versatile tool that can be utilized for a wide range of applications, such as population research, taxonomy and phylogenetic studies, germline characterization, breeding, and trait mapping, even in plants with complex genomes.

6.5.2 *Whole Genome Resequencing (WGR) Technique*

Whole genome sequencing (WGS) involves the initial assembly of the complete genome sequence, while WGR is employed to evaluate genomic diversity within individuals or populations (Bhat et al., 2020). WGR requires a preexisting reference genome in order to perform mapping and identify genetic variants. De novo WGS is the procedure of completely reconstructing the genetic material of a species from scratch, without any prior reference genome (Sevanthi et al., 2018). Contrary to the WGS, WGR enables the examination of the diverse sequences present in an individual's or a population's genome. Prior to doing read mapping, it is important to possess the genomic sequence of the species in question, as stated by Kumawat et al. (2022).

6.5.3 *Whole Exome Sequencing Approach*

Transcriptome analysis is an important tool for identifying crucial genes for breeding selection. Recent advancements in long-read technology have greatly improved the efficiency of analyzing complicated transcriptomes. This technique allows for the accurate collection of all full-length transcripts, including splice variants (Rangan et al., 2017). Whole-exome sequencing enables the detection of genetic

variants specifically in the areas of DNA that code for proteins. This technique improves the ability to identify mutations in the target gene that are responsible for generating diseases. The cost-effectiveness of this strategy is derived from the fact that it focuses on sequencing specific regions of interest rather than the entire genome. The scope of this approach is broadened to encompass the entire functional portion of a genome, which includes noncoding genes as well as regulatory elements like promoters and enhancers (Warr et al., 2015).

The introduction of NGS has made it easier to construct reference genomes for many different crop species, which serves as a framework for future genetic research. In addition, improvements in sequencing technologies have resulted in the emergence of transcriptomics, epigenomics, and metagenomics methods. These approaches allow for a comprehensive comprehension of gene expression, epigenetic changes, and microbial interactions in agricultural systems.

Overall, the combination of high-throughput sequencing, GWAS, and molecular marker technologies has significantly transformed gene mapping endeavors in agricultural genomics. These sophisticated instruments enable scientists to decipher the genetic foundation of climate resistance in crops and expedite the creation of climate-adaptive cultivars crucial for sustainable agriculture during a shifting climate.

6.6 Beyond Genetic Mapping: Other Approaches to Climate-Resilient Crops

6.6.1 Marker-Assisted Breeding

Marker-assisted breeding technologies have become increasingly popular and are considered superior to traditional breeding techniques. Breeding involves identifying and mapping QTLs/genes and selecting genetic materials directly or indirectly (Singh & Singh, 2015). Classical indicators and molecular markers are plant biomarkers.

Marker-assisted breeding (MAB) uses molecular markers for drought tolerance, heat resistance, and disease resistance to select plants with desired genetic traits. By integrating multi-armed bandit (MAB) algorithms into breeding programs, researchers can accelerate the process of creating crop varieties that are resilient to stress, while also preserving genetic variety. This methodology improves the effectiveness and accuracy of breeding, ultimately resulting in the growth of crops that can withstand and flourish under challenging environmental conditions.

6.6.2 *Gene Editing Techniques*

Gene editing technologies, including CRISPR-Cas9 and other genome editing techniques, have great potential for enhancing the resilience and adaptability of crops in the face of climate change. These approaches allow for precise modifications to the genetic composition of plants, enabling scientists to add beneficial traits or adjust existing genes associated with the capacity to endure stress. Gene editing enables the precise targeting of certain genetic loci in order to create crops with heightened drought tolerance, heightened heat resistance, or greater capacity to withstand high levels of salinity.

The CRISPR/Cas9 system is based on adaptive immunity in bacteria and archaea. This technique uses acquired viral sequences to direct an endonuclease to destroy viral genomes seen again. Traditional genome editing uses a 20-nucleotide artificial guide RNA (gRNA) sequence. This sequence and the Cas9 nuclease produce a complex that targets a DNA region. A double-stranded break (DSB) occurs at that DNA sequence (Makarova et al., 2020). The use of CRISPR/Cas9 knockouts showed that certain genes had a direct association with the regulation of yield attributes, as reported by Kouhen et al. (2023). The study by Fu et al. (2019) revealed that the significant QTL qLL9, which affects the length of rice leaves, is the same gene as DEP1. This discovery opens up possibilities for combining other advantageous genes similar to qLL9. Shen et al. (2018) found that manipulating the grain number and grain size QTLs (Gn1a and GS3) had distinct impacts on grain production, which varied depending on the individual variety.

Before genome editing became available, functional genomics depended on laborious and time-consuming methods such as T-DNA insertion tagging and traditional mutagenesis techniques (Feng & Mundy, 2006). The CRISPR/Cas9 technique offers an effective approach to creating extensive and well-defined collections of mutant plants. The initial application of this technology was demonstrated in rice by Meng et al. (2017). Gene editing provides benefits compared to conventional breeding techniques as it enables accurate modifications to the plant's DNA without the introduction of external genetic material. This technology has the potential to expedite the creation of crop types that are resistant to climate change and specifically designed to endure the difficulties caused by shifting environmental circumstances.

6.6.3 *Transcriptomics*

Transcriptomics is essential for comprehending the molecular pathways that drive stress responses in crops. This method entails a thorough examination of gene expression patterns by investigating the transcriptome, which refers to the entirety of RNA transcripts generated by a cell or organism. Transcriptomic studies offer valuable insights into the mechanisms by which plants control gene expression

during stressful conditions, enabling researchers to pinpoint crucial genes and pathways that contribute to stress tolerance.

An examination of transcriptome data can provide valuable insights into the mechanisms by which plants maintain a delicate equilibrium between growth and survival when faced with abiotic stress conditions. Plants can respond to various environmental stresses such as drought, high temperatures, salinity, metal toxicity, and other nonliving factors by adjusting their physiological, biochemical, molecular, and cellular processes. They can actively alter their gene expression patterns, activate mechanisms to tolerate stress, or regulate their biological functions to adapt to unfavorable living conditions (Wang et al., 2020).

Through the process of analyzing the transcriptome landscape of genes that respond to stress, scientists can determine which genes should be given priority for further inquiry and potential alteration. Transcriptomics allows for the identification of biomarkers linked to stress tolerance and aids in the creation of crop varieties that are more resistant to environmental stresses. Transcriptome technology facilitates the rapid identification of stress-related defense components and elucidates the interplay between metabolic pathways, signal transduction, and defense response. The findings of Wang et al. (2020) have important implications for improving plant stress resistance and understanding the underlying process.

6.6.4 Epigenomics

The transcriptional and post-transcriptional control of gene expression is extremely crucial for the survival of plants. Plants have created a number of different ways to adapt to their environment. The word “epigenetics” was first used by Waddington (1942) to describe the interactions between genes and their environments. According to Wu and Morris (2001), the phrase is now used to refer to hereditary gene function alterations that occur without any changes to the DNA sequence. Specifically, DNA methylation, histone post-translational modifications, and the production of small RNA are the factors that are responsible for these alterations (Agarwal et al., 2020). There are a number of epigenetic mechanisms that influence how plants react to biotic and abiotic stress. These mechanisms include DNA methylation, alterations to histone proteins after translation, and the control of noncoding RNA genes. DNA methylation is a process where cytosine molecules are modified by DNA methyltransferases. This process is important for maintaining the stability of the genome and the structure of chromatin. It also affects the accessibility of genes and the regulation of transcription. The alteration of cytosine methylation patterns caused by stress has been associated with the regulation of genes involved in plant stress responses, emphasizing its dynamic function in adaptation (Yong-Villalobos et al., 2015).

Epigenetic modifications of histones: Histone changes, such as acetylation and methylation, control the rearrangement of chromatin structure and regulate gene expression. H3K9 and H3K27 methylation patterns determine whether genes are

repressed or activated, playing a role in regulating stress-responsive genes and maintaining heterochromatin states in plants (Liu et al., 2010). Enzymes such as HATs, HDACs, and HDMs are responsible for carrying out these alterations in response to various stress signals (Ueda & Seki, 2020). The RNA species indicated have a crucial function in modulating plant stress adaption via controlling stress-responsive genes, as evidenced by Ito et al. (2011).

These epigenetic processes together control gene expression networks in plants when they are under stress. This allows plants to adapt and perhaps improve their ability to withstand environmental challenges. Comprehending the complex workings of these processes offers the potential for creating innovative approaches to cultivating crops that can withstand stress (Tan & Rodríguez López, 2023).

Researchers can find epigenetic markers linked to stress tolerance and learn how plants respond to stress through the study of epigenetic regulation. Utilizing epigenomic knowledge can guide breeding approaches focused on creating climate-resistant crops with consistent and inheritable features for stress tolerance.

6.6.5 *Metabolomics*

Metabolomics is a field that examines the complete study of metabolites, which are tiny chemicals generated by biological activities, in reaction to environmental stimuli. This technique offers significant insights into the biochemical processes and metabolic networks that regulate stress responses in crops. To understand the complex changes in metabolites between interconnected species, scientists utilize the area of metabolomics, which thoroughly examines all the metabolites found in a specific biological system. Currently, analytical approaches, particularly for plants and microbial metabolomes, are unable to achieve the goal of metabolomics, as stated by Olanrewaju et al. (2024).

Metabolomic profiling enables researchers to identify metabolites and metabolic signatures that are related to stress and specifically associated with certain stress scenarios. Scientists can find metabolic targets for crop development by comprehending how plants adjust their metabolism in response to stress. Metabolomics aids in the advancement of climate-resilient crops by directing breeding endeavors to raise stress tolerance and optimize metabolic pathways for better adaptation to evolving environmental conditions.

6.6.6 *Potential Synergies Between Different Methods*

The possible interactions between genetic mapping, marker-assisted breeding, and gene editing offer favorable prospects for improving the ability of crops to withstand climate challenges. Each of these methods offers unique benefits to the

creation of climate-resistant plant types, and combining them can greatly speed up attempts to improve crops.

6.6.6.1 Genetic Mapping: Comprehensive Comprehension of Desired Characteristics

Genetic mapping studies establish the foundation for finding genes (Leppert, 1990) and specific areas of the genome that are linked to favorable characteristics related to climate resilience, such as the ability to withstand drought, resist high temperatures, and tolerate salinity. Genetic mapping is a valuable tool for understanding the genetic makeup of complex traits, which helps in developing effective breeding techniques.

6.6.6.2 Marker-Assisted Breeding: Harnessing Genetic Information

Marker-assisted breeding (MAB) incorporates genetic mapping information into breeding programs by utilizing molecular markers that are associated with certain qualities of interest. These markers function as indicators of advantageous genetic differences that can be swiftly and precisely chosen during breeding procedures. Breeders can effectively evaluate and choose plants with the appropriate genetic characteristics by including markers linked to climate resilience qualities.

Gene editing technologies are advanced tools used to make precise modifications to the genetic material of organisms. Gene editing tools, such as CRISPR-Cas9, allow for accurate alterations to particular genes linked to climate adaptation. Scientists can add advantageous genetic variations or modify existing genes to improve stress tolerance in crops. Gene editing enhances genetic mapping and marker-assisted breeding by enabling breeders to directly change genetic elements that contribute to climate resistance features.

6.6.6.3 Integrating Approaches: A Thorough Understanding of Resilience Mechanisms

Genetic mapping, marker-assisted breeding, and gene editing, together with omics technologies like transcriptomics and metabolomics, enhance our understanding of the molecular processes that regulate climate resilience in crops. Transcriptomic studies provide insight into the control of genes during stressful periods, identifying essential pathways and genes involved in stress responses. Metabolomic profiling provides useful insights into the metabolic changes associated with stress adaptation.

Through the integration of various methodologies, scientists acquire an extensive understanding of the interplay between genes and the environment, as well as the intricate systems that regulate stress tolerance. The utilization of a multidisciplinary approach allows for the creation of comprehensive methods to enhance crop quality.

This technique expedites the production of personalized crop varieties that are specifically designed to thrive in certain agroecological conditions and overcome environmental obstacles. In summary, the integration of genetic mapping, marker-assisted breeding, gene editing, and omics technologies holds significant promise for strengthening the durability and adaptability of crops in the face of climate problems. By employing these integrated techniques, the development of crop types that are resilient to climate change is expedited, thereby fostering sustainable agriculture and guaranteeing food security.

6.7 Conclusion

Genetic mapping and other methods are crucial in creating crops that can withstand the increasing effects of climate change on farming. Thanks to genomic mapping, important genes and genetic markers linked to adaptation to climate change, including heat tolerance, disease resilience, and drought tolerance, have been identified. With this newfound information, breeders can use marker-assisted breeding and gene editing techniques to create more tolerant crop types faster.

6.8 Future Perspective

In the face of the complex difficulties posed by climate change in agriculture, we must take immediate and coordinated action to make significant strides towards sustainable solutions. Ongoing research endeavors will expedite the discovery of pivotal genes and molecular pathways that underlie characteristics like drought tolerance, heat resistance, and salinity tolerance. This understanding is essential for expediting the progress of developing climate-resilient crop types that can endure the effects of shifting environmental circumstances. Furthermore, the promotion of technology transfer and the encouragement of the general use of new agricultural techniques are crucial measures for integrating climate-resilient crop types into mainstream agriculture. Agricultural practitioners should be provided with the means and knowledge to employ state-of-the-art technologies and climate-resilient methods that improve efficiency and reduce adverse effects on the environment. Furthermore, it is crucial to cultivate cooperative alliances across academia, industry, and government organizations.

It is crucial to advocate for laws and regulatory frameworks that provide support. Governments and policymakers have a crucial role in encouraging sustainable agriculture practices and the uptake of climate-resilient technologies.

Finally, it is crucial to invest in capacity building and education initiatives to provide farmers with the necessary information and skills to properly use climate-smart farming approaches. Enhancing the farmers' capacity through training and

education enables them to effectively respond to climatic problems and embrace sustainable farming techniques.

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Chapter 7

Radiation-Induced Effects and Stress-Induced Mutagenesis for the Resilience in Crops



Prasann Kumar, K. Jaiysuriyan, and B. Gopika

7.1 Background

The worldwide agricultural terrain is currently experiencing significant changes, influenced by many challenges that threaten both food security and the sustainable cultivation of crops (Wassermann et al., 2022). Environmental factors, such as climate changes and soil deterioration, continuously pressure agricultural ecosystems. This highlights the need for a more comprehensive understanding of the mechanisms to help crops withstand and recover from these challenges. Scientists have recently concentrated on the complex interaction between radiation-induced effects and stress-induced mutagenesis as possible factors that drive crop adaptive responses (Aggarwal et al., 2024; Devos et al., 2024; Ray & Jangid, 2023). This exploration aims to unravel the intricate molecular structures of these phenomena, revealing their significance in enhancing crop resilience and potentially transforming agricultural practices. Agriculture, the fundamental pillar of human civilisation, has encountered numerous challenges. Nevertheless, the current situation is characterised by a unique combination of factors that present substantial risks to crop productivity. Climate change disrupts conventional growing conditions by introducing unpredictable weather patterns and severe events. Simultaneously, human activities contribute to soil deterioration, water scarcity and the rapid increase of pests and diseases. These challenges require inventive strategies to guarantee the durability of crops, allowing them to flourish in unfavourable conditions. Crop resilience refers to the complex capacity of plants to endure and adjust to environmental pressures while sustaining productivity and nutritional value. Durable crops can enhance food security by exhibiting greater resilience to erratic climatic phenomena and enduring the challenges posed by a constantly evolving agricultural environment.

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Understanding the molecular mechanisms that dictate resilience is essential for developing crop varieties that flourish in demanding conditions (Ganapathy et al., 2021; Imran & Ghosh, 2024; Mushtaq et al., 2018; Schröder et al., 2019). Radiation, whether it occurs naturally or is caused by human activities, is a widespread environmental factor that has not been thoroughly studied about the ability of crops to withstand and recover from stress. Natural sources include cosmic rays and terrestrial radioactivity, whereas anthropogenic sources encompass nuclear activities and electromagnetic radiation. Observations have been made regarding the impact of radiation on crops, specifically in terms of their morphology, physiology and molecular composition. Exposure to radiation causes stress in plant cells, initiating a series of reactions. These reactions result in modifications to growth patterns, changes in metabolic processes and activating pathways that respond to stress. Gaining a comprehensive understanding of the influence of radiation on crops is crucial not only for minimising potential damage but also for harnessing its beneficial effects. Although excessive radiation can be harmful, studies have shown that moderate exposure can trigger hormesis, which is a process where low levels of stressors stimulate adaptive responses, ultimately improving the overall resilience of the organism. Understanding the inherent duality of radiation, both as a source of stress and a potential catalyst for advantageous outcomes, is essential for maximising its effectiveness in agriculture (Ali et al., 2022; Egea et al., 2022; Hossain et al., 2021; Smith et al., 2023; Turan Büyükdinç et al., 2022). Simultaneously, stress-induced mutagenesis has become a captivating approach to investigate the adaptive responses of plants when confronted with environmental challenges. This phenomenon entails initiating mutagenic pathways as a response to stress, resulting in heightened genetic diversity among populations. The mutagenic processes encompass mechanisms of error-prone DNA repair, the induction of mutagenic enzymes and various genetic rearrangements. Stress-induced mutagenesis is believed to play a role in the production of phenotypic variation, potentially aiding the adaptation of crops to evolving environmental circumstances. Various environmental stressors, including abiotic factors such as extreme temperatures, drought and nutrient limitations, as well as biotic factors like pathogen attacks, can induce stress-induced mutagenesis (Kaul et al., 2024; Kumar et al., 2021; Leung & An, 2004; Muha-Ud-Din et al., 2024; Zhang et al., 2023). As a result, genetic diversity provides a valuable source of potential adaptations that can be chosen in response to changing conditions, offering a fascinating opportunity for enhancing crop improvement and resilience. As we explore the connection between the effects caused by radiation and the mutagenesis induced by stress, it becomes clear that these two phenomena may overlap. Radiation exposure can induce environmental stress, leading to stress-induced mutagenesis as a plant's adaptive mechanism. This adds intricacy to our comprehension of how plants react to environmental difficulties. In the following sections of this investigation, we will analyse the origins and impacts of radiation on crops, uncover the mechanisms that govern mutagenesis caused by stress, and clarify the potential interaction between these two phenomena. The objective is to expand our theoretical comprehension and investigate practical implementations that utilise these processes to achieve sustainable crop production in response to a

constantly evolving agricultural environment (Biswal et al., 2019; Khatri et al., 2023; Manzanares et al., 2016; Molitorisová et al., 2024).

7.2 Significance of Radiation-Induced Effects and Stress-Induced Mutagenesis

Radiation-induced effects and stress-induced mutagenesis are complex aspects of how plants respond to environmental challenges. They play essential roles in shaping the adaptive strategies of crops. Although radiation is commonly seen as a possible danger, it can also function as a stressor that, when controlled, produces advantageous effects through hormesis. Simultaneously, stress-induced mutagenesis, prompted by diverse environmental stressors, is an adaptive mechanism that increases genetic diversity within populations, potentially resulting in enhanced crop resilience. This investigation examines the importance of these occurrences, elucidating their dual characteristics and potential uses for strengthening agricultural resilience (Table 7.1).

Table 7.1 Significance of radiation-induced effects and stress-induced mutagenesis

Inducing factor	Radiation-induced effects	Stress-induced mutagenesis effects
Ionising radiation	– DNA strand breaks	– Increased mutation rates
	– Chromosomal aberrations	– Activation of error-prone repair pathways
	– Point mutations	– Stress-induced hypermutation
UV radiation	– Thymine dimers	– DNA replication errors
	– DNA cross-linking	– Induction of transposons
	– Mutations in skin cells	– Increased recombination rates
Chemical stressors	– DNA adduct formation	– Base pair substitutions
	– DNA interstrand crosslinks	– Frameshift mutations
	– Alkylation of DNA bases	– Induction of mobile genetic elements
Oxidative stress	– DNA oxidation	– Oxidative damage to DNA
	– Guanine oxidation	– DNA double-strand breaks
	– Lipid peroxidation	– Activation of repair mechanisms
Heat stress	– Denaturation of DNA strands	– Increased transcription errors
	– Protein misfolding	– Formation of reactive oxygen species
	– DNA helix destabilisation	– Activation of DNA repair pathways
Nutritional stress	– DNA methylation changes	– Induction of mobile genetic elements
	– Alterations in nucleotide pools	– Point mutations
	– Impaired DNA repair mechanisms	– Genome instability

(Source: Biswal et al., 2019; Khatri et al., 2023; Manzanares et al., 2016; Molitorisová et al., 2024)

Agricultural radiation exposure originates from both natural and human-caused sources (Bhatnagar-Mathur et al., 2015; Cui, 2023; Liu et al., 2023; Marwein et al., 2019; Shahwar et al., 2023). Cosmic radiation and terrestrial radioactivity are natural sources, whereas nuclear activities such as power generation and medical applications fall under anthropogenic sources. It is essential to assess the potential impacts by understanding the levels and types of radiation crops are exposed to, as their proximity to these sources can vary (Fig. 7.1).

Plants in certain situations, such as regions with heightened levels of natural radiation, have developed mechanisms to deal with ongoing exposure. Nevertheless, when plants are exposed to levels of a substance that exceed specific limits, whether for a short period or over a long period, they can experience stress reactions that result in changes to their physical structure, biological functions and genetic makeup. Physiological manifestations of radiation-induced stress can occur in diverse ways. Morphological alterations may encompass modified growth patterns, diminished leaf surface and modifications in reproductive structures (Afzal et al., 2020; Chengqi et al., 2023; Deoli & Hasenstein, 2018; Enders & Begcy, 2021; Khah et al., 2024; Singh et al., 2024). Observations of altered nutrient uptake, photosynthesis disruptions, water-use efficiency changes and radiation stress responses have been made. The responses to radiation exposure vary depending on the context, with different plant species showing unique reactions. The molecular level is where the effects of radiation-induced stress are controlled through intricate signalling pathways. Radiation exposure can lead to DNA damage, which triggers the activation of repair mechanisms. The response entails stimulating stress-responsive genes, initiating antioxidant defences and adjusting hormone levels. In addition, there is a correlation between low radiation levels and hormetic effects, which refers to the stressor triggering adaptive responses that ultimately improve the plant's overall resilience. Understanding the intricate molecular mechanisms underlying radiation-induced stress is crucial for distinguishing harmful and advantageous effects. Exploiting the beneficial effects of stress caused by radiation can be utilised to

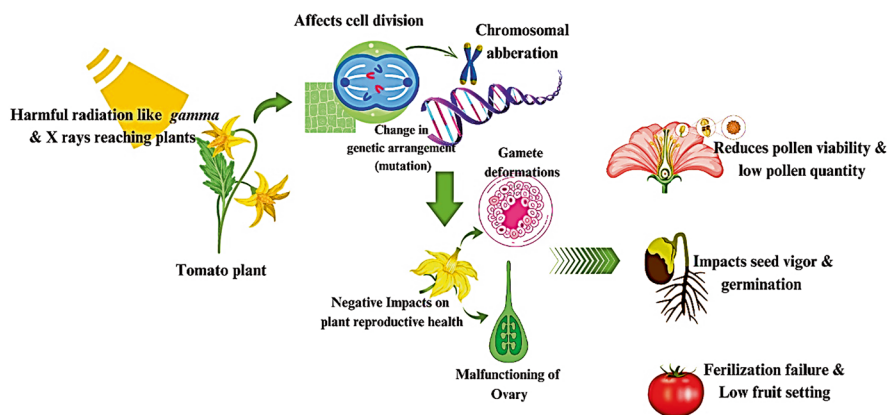


Fig. 7.1 Impact of radiation on the reproduction of plants

cultivate crops with improved ability to withstand environmental difficulties. Stress-induced mutagenesis is when exposure to environmental stressors activates mechanisms that enhance the genetic diversity within a population. This adaptive response is especially pertinent in the field of agriculture, where crops encounter a multitude of stressors, including both abiotic and biotic factors. Abiotic stressors encompass environmental factors such as extreme temperatures, drought, lack of nutrients and, as examined in this context, radiation exposure. Biotic stressors include pathogen assaults, herbivore invasions and resource competition. Although the stressors that cause mutagenesis in plants can vary, they all share the purpose of enabling rapid adaptation to change conditions. Stress-induced mutagenesis is a process that allows for the creation of genetic diversity, which can then be influenced by natural selection. This can result in developing traits more adapted to the current environmental conditions (Jiang et al., 2024; Meshram et al., 2022; Shohael & Hefferon, 2023; Sivasankar et al., 2021; Zhao et al., 2022). Stress-induced mutagenesis in plants involves complex interactions within the plant's genome. Stress can cause DNA damage, and instead of depending only on accurate repair mechanisms, stress-induced mutagenesis involves repair pathways that are prone to errors. These pathways induce alterations, additions or removals in the DNA sequence, resulting in genetic variation within the population. Moreover, stress-induced mutagenesis may entail the stimulation of particular enzymes possessing mutagenic characteristics. These enzymes facilitate the introduction of genetic variations that could provide benefits in stressful circumstances. The malleability of plant genomes in response to stress-induced mutagenesis offers a pool of potential adaptations that can be investigated for enhancing crop quality. The importance of stress-induced mutagenesis in crop adaptation lies in its ability to produce phenotypic diversity, which is the foundation for natural selection. Genetic variability can be especially advantageous in environments that undergo rapid changes. Stress-induced mutagenesis increases the frequency of mutations more than spontaneous mutations, thereby speeding up the rate at which populations adjust to new and difficult conditions. Stress-induced mutagenesis has the potential to be a useful approach for enhancing crops in agricultural environments. Through subjecting crops to carefully regulated stress conditions, scientists can deliberately trigger specific genetic modifications that could result in desirable characteristics such as increased resilience to drought, immunity to particular pathogens or improved utilisation of nutrients. Gaining insight into the function of stress-induced mutagenesis in crop adaptation unveils novel prospects for breeding tactics focused on cultivating robust crop varieties. The convergence of radiation-induced effects and stress-induced mutagenesis adds an intriguing aspect to our comprehension of how plants react to environmental challenges. Although radiation is typically seen as a source of stress, it can trigger hormesis, enhancing plants' adaptive reactions by intersecting with stress-induced mutagenesis (Ahmar et al., 2023; Jaradat, 2016; Maushe et al., 2023; Sharma et al., 2021; Singh et al., 2021; Suparmaniam et al., 2024). This collaboration has the potential to lead to crops that have improved ability to withstand various environmental stressors, making them more resilient. The interaction between radiation and stress responses creates complexity in plants' adaptive mechanisms. The stress caused by radiation

triggers pathways that coincide with those triggered by other environmental stressors. Comprehending the similarities and differences in these routes is crucial for unravelling the complex network of reactions that contribute to the ability of crops to withstand challenges. Case studies and experimental evidence offer valuable insights into the interaction between radiation-induced effects and stress-induced mutagenesis. Scientists have performed experiments that exposed crops to carefully regulated radiation levels and observed the resulting alterations in stress responses and mutagenic processes. These studies contribute to our theoretical comprehension and provide practical ways to utilise these phenomena to enhance crop resilience. Formulating tactics to utilise radiation's beneficial impacts on crops necessitates meticulous adjustment of exposure levels. Systematic exposure to low radiation levels can trigger hormesis, which prepares plants for increased stress tolerance (Gao et al., 2023; Goyal et al., 2023; Kheya et al., 2023; Peñas et al., 2023; Sonkar et al., 2023; Ul Haq et al., 2022). By incorporating radiation exposure into agricultural practices, particularly in the early stages of growth, cultivating crops with increased resilience is possible (Fig. 7.2).

Controlled induction of stress-induced mutagenesis is a valuable tool in crop breeding programmes. By subjecting crops to specific stressors, breeders can deliberately induce genetic alterations that may result in favourable characteristics. The integration of conventional breeding methods with stress-induced mutagenesis expedites the rate of crop enhancement, providing a focused strategy for cultivating varieties that are more suited to environmental adversities. Incorporating the consequences of radiation exposure and stress-induced genetic changes into agricultural methods is consistent with the objectives of sustainable agriculture. Developing robust crop varieties decreases the need for external inputs like pesticides and fertilisers, promoting environmentally sustainable and economically feasible farming methods. The potential of crops that can flourish in various and demanding conditions is especially pertinent in the context of climate change and the necessity for robust food systems (Ganapathy et al., 2021; Hossain et al., 2021; Manzanares et al., 2016; Muha-Ud-Din et al., 2024; Mushtaq et al., 2018; Smith et al., 2023; Wassermann et al., 2022).

Although there has been some progress in comprehending the importance of radiation-induced effects and stress-induced mutagenesis, there are still significant gaps in our understanding. Deciphering the comprehensive underlying mechanisms is challenging due to the intricate interplay of genetic, physiological and environmental factors. Additional investigation is required to examine particular routes, ascertain crucial genes and decipher the molecular occurrences that regulate these phenomena. Given the ongoing investigation into the potential uses of radiation-induced effects and stress-induced mutagenesis, it is crucial to prioritise ethical considerations and safety concerns. It is essential to prioritise the safety of consumers and the environment, particularly when implementing genetic modifications in crops. Ethical frameworks and regulatory guidelines should guide responsible utilisation of these technologies to prevent unintended consequences. The potential advancements in radiation-induced effects and stress-induced mutagenesis research offer the possibility of transformative breakthroughs that could significantly enhance

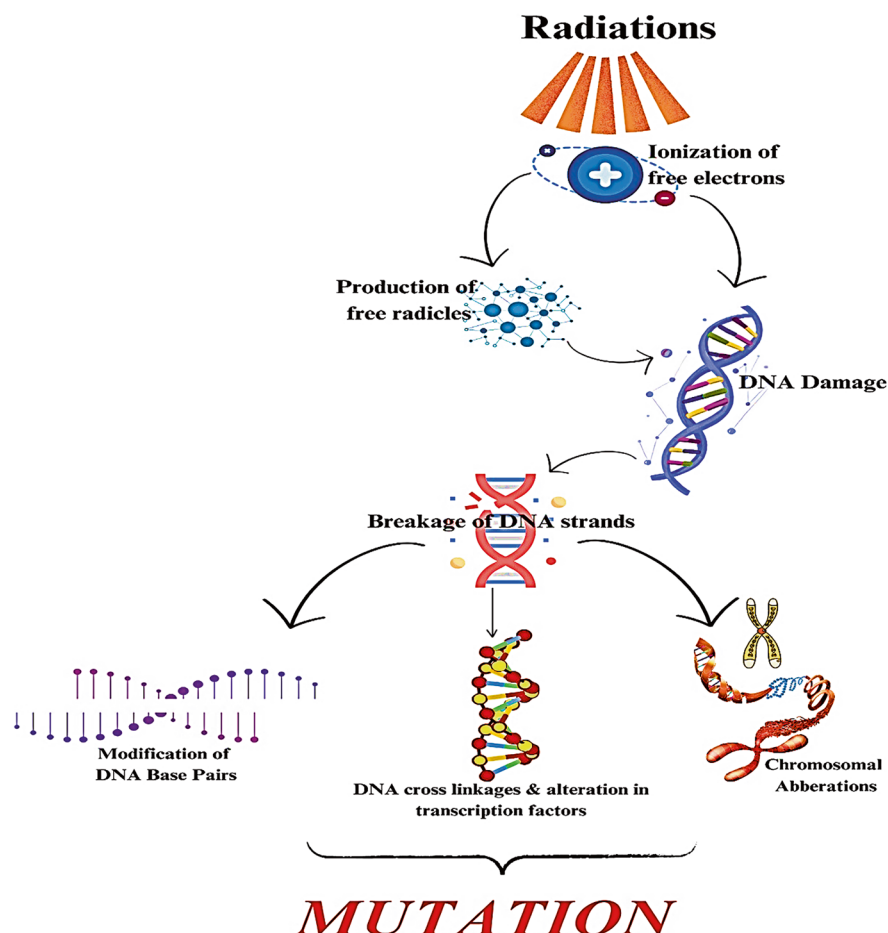


Fig. 7.2 Radiation-induced mutations: understanding the impact on agricultural crops

crop resilience. Exploring the intricacies of particular stressors, discovering additional molecular pathways and improving methods for controlled mutagenesis induction are promising areas for investigation (Cui, 2023; Enders & Begcy, 2021; Jiang et al., 2024; Khah et al., 2024; Leung & An, 2004; Marwein et al., 2019; Zhang et al., 2023). The synergy between plant biologists, geneticists and agronomists is essential for progressing our understanding and its application in practical agricultural solutions. Overall, the importance of radiation-induced effects and stress-induced mutagenesis in enhancing the resilience of crops is complex. Radiation, typically seen as a possible danger, has a two-fold characteristic. When used correctly, it can stimulate hormesis and improve the ability of plants to adapt. Simultaneously, stress-induced mutagenesis creates variations in the genetic makeup, allowing crops to quickly adjust to shifting environmental circumstances.

The interaction between radiation-induced effects and stress-induced mutagenesis complicates our comprehension of plant reactions to environmental stressors. This intersection creates opportunities for developing crop varieties that have improved resilience and can withstand various challenges in agriculture. As we deal with the difficulties and possibilities brought about by these occurrences, we must consider ethical considerations, safety concerns and sustainable farming practices. Incorporating the impacts of radiation-induced effects and stress-induced mutagenesis into crop breeding programmes shows potential for creating robust varieties that can help ensure global food security. To fully harness the potential of these phenomena for the benefit of present and future generations, scientists, policymakers and the agricultural community must collaborate closely throughout this exploratory journey (Chengqi et al., 2023; Goyal et al., 2023; Jaradat, 2016; Shohael & Hefferon, 2023; Suparmaniam et al., 2024; Ul Haq et al., 2022; Zhao et al., 2022).

7.3 Radiation-Induced Effects on Agricultural Crops

Radiation, commonly linked to potential damage, has a multifaceted role in the agricultural environment. The impact of radiation exposure on crops in agriculture can vary, with both natural and human-caused sources playing a role (Biswal et al., 2019; Devos et al., 2024; Egea et al., 2022; Imran & Ghosh, 2024; Khatri et al., 2023; Molitorisová et al., 2024; Smith et al., 2023; Turan Büyükdinç et al., 2022). These effects can range from stress-induced reactions to potential benefits through hormesis. Knowledge about the origins and effects of radiation on crops is essential for devising strategies that harness its beneficial aspects while minimising potential damage. This study investigates the impact of radiation on crops, analysing both natural and human-caused sources and their consequences on the ability of crops to withstand and produce. The radiation exposure in agriculture can be ascribed to two primary sources: natural and anthropogenic (Fig. 7.3).

Both factors contribute to the total radiation background that crops are exposed to, influencing their responses and their growth and development. Cosmic radiation is generated in the depths of outer space and consistently bombards the Earth's atmosphere. Although most cosmic radiation is absorbed by the atmosphere, a small portion manages to penetrate and reach the Earth's surface. Throughout their growth, crops are subjected to this form of radiation, with the intensity varying depending on factors such as altitude and geographic location. The influence of cosmic radiation on crops is deemed minimal, as plants have developed mechanisms to handle sustained exposure. Fluctuations in cosmic radiation levels can impact plant physiological processes, potentially leading to adaptive responses (Chengqi et al., 2023; Deoli & Hasenstein, 2018; Jiang et al., 2024; Maushe et al., 2023; Shohael & Hefferon, 2023; Sivasankar et al., 2021; Sonkar et al., 2023; Suparmaniam et al., 2024). Further investigation into the interaction between cosmic radiation and crop resilience is a captivating field of study. Radioactive elements found in the Earth's crust contribute to the occurrence of terrestrial

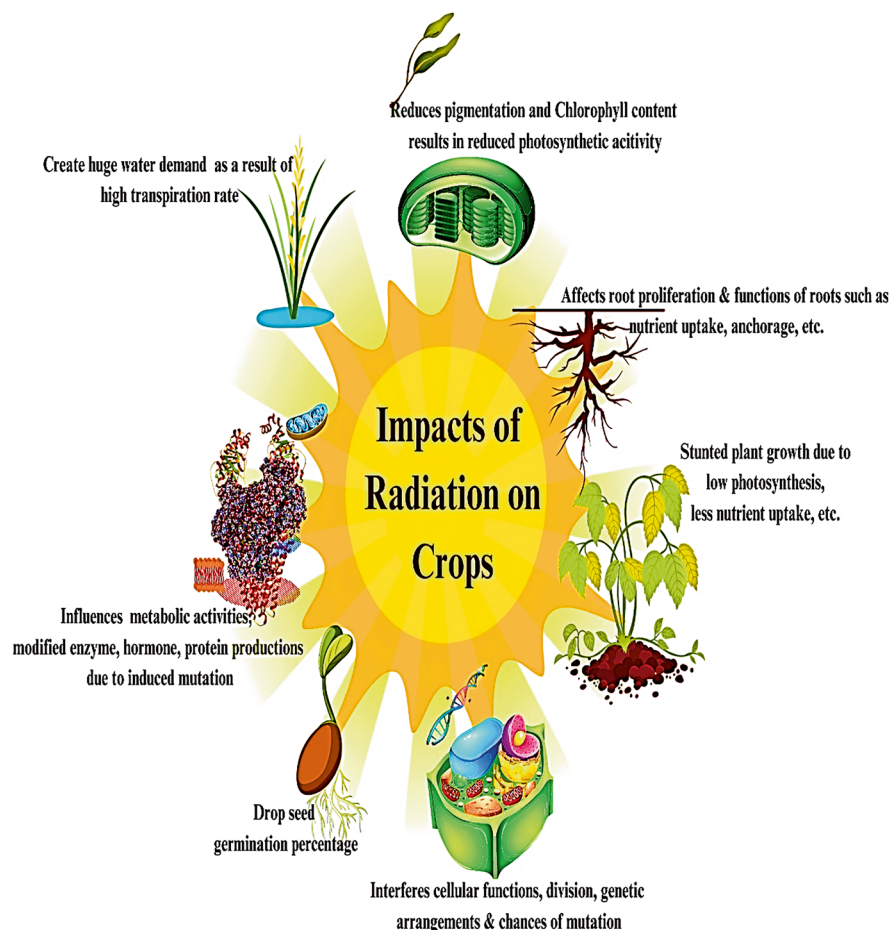


Fig. 7.3 Impact of radiation on crops

radioactivity. Radionuclides that occur naturally, such as uranium, thorium and potassium-40, undergo radioactive decay and release radiation. The concentration of these radionuclides is influenced by the soil composition and geological characteristics, resulting in spatial variations in terrestrial radioactivity. Plants assimilate radionuclides from the soil during the process of absorbing nutrients. The influence of terrestrial radioactivity on crops is contingent upon the particular radionuclides present, their levels of concentration and the type of plant species. Certain plants have developed mechanisms to selectively gather or prevent the absorption of specific radionuclides, affecting their sensitivity to radiation. Comprehending the complex connections between land-based radioactivity and crop reactions is crucial for evaluating possible effects on agricultural output and food security. The proliferation of nuclear power generation has introduced human-caused radiation sources

into the farm environment. Nuclear power plants emit low-level radioactive substances into the atmosphere and water during regular operations. Accidents or leaks from these facilities can result in elevated levels of radioactive contamination in the surrounding areas, impacting agricultural lands and crops (Imran & Ghosh, 2024; Khatri et al., 2023; Molitorisová et al., 2024; Muha-Ud-Din et al., 2024; Smith et al., 2023). The influence of radiation emitted by nuclear power plants on crops is contingent upon variables, such as the proximity to the origin, the nature of the radionuclides discharged and prevailing meteorological conditions. Surveillance and reducing the impact of possible pollution are crucial to guarantee agricultural goods' safety and consumers' welfare. Anthropogenic radiation exposure in agriculture is increased by the utilisation of radioactive materials in medical and industrial practices (Bhatnagar-Mathur et al., 2015; Kaul et al., 2024; Khah et al., 2024; Leung & An, 2004; Liu et al., 2023; Marwein et al., 2019; Shahwar et al., 2023). Diagnostic and therapeutic procedures that employ radioactive tracers or isotopes have the potential to emit radiation into the surrounding environment. Likewise, industrial processes such as radiography, irradiation and sealed sources can potentially introduce radiation into agricultural environments. The influence of radiation originating from medical and industrial sources on crops is contingent upon variables such as proximity, the radiation emitted and the effectiveness of containment measures (Table 7.2).

Ensuring the safe handling and disposal of radioactive materials is essential to prevent the contamination of agricultural lands and maintain the safety of the food supply chain. Crops can exhibit morphological changes as a result of stress induced by radiation. These alterations can frequently be detected at different phases of plant maturation, impacting the overall growth patterns and structural traits. Exposure to elevated radiation levels, particularly ionising radiation, can inhibit crop growth. This can be attributed to radiation's influence on cell division and elongation processes. Radiation exposure can harm the meristematic tissues, which play a crucial role in plant development, decreasing plant height and overall biomass (Ahmar et al., 2023; Gao et al., 2023; Jiang et al., 2024; Maushe et al., 2023; Meshram et al., 2022; Singh et al., 2021; Sonkar et al., 2023). Plant reproductive structures, such as flowers and seeds, are susceptible to stress caused by radiation. Elevated radiation levels can result in irregular growth in the growth of flowers, which can impact the pollination process and the formation of seeds. These factors can affect the amount of crops produced and the ability to reproduce successfully. Crops experience a series of physiological responses when exposed to radiation-induced stress. These responses are coordinated at the cellular and molecular levels, affecting various metabolic processes crucial for the survival of plants. Radiation-induced stress can disrupt photosynthesis, a crucial process for plant growth. Radiation exposure can lead to alterations in chlorophyll content, photosynthetic pigments and the activity of photosynthetic enzymes. These interruptions can impact the effectiveness of plants' conversion of energy and absorption of nutrients. Radiation exposure can affect how plants absorb and use important nutrients. Alterations in ion transport mechanisms and nutrient absorption can result in imbalances in nutrient concentrations within plant tissues. These modifications can affect the overall well-being of

Table 7.2 Radiation type and its exposure effect on crops

Radiation type	Exposure effects on agricultural crops
Ionising radiation	– Genetic mutations in crop DNA, potentially leading to altered traits or phenotypes
	– Inhibition of cell division, affecting growth and development
	– Reduction in crop yield due to damage to reproductive structures
	– Changes in photosynthetic efficiency and overall plant metabolism
	– Increased susceptibility to diseases and pests
UV radiation	– Impact on seed germination and viability
	– DNA damage, particularly in the form of thymine dimers
	– Reduction in chlorophyll content, affecting photosynthesis
	– Altered pigment production and composition
Gamma radiation	– Increased risk of sunburn and tissue damage
	– Induction of random mutations in the plant genome
	– Inhibition of cell division and overall growth
	– Disruption of physiological processes, leading to nutrient imbalances
	– Delayed flowering and maturation
X-ray radiation	– Impact on seed germination and seedling development
	– Similar effects to gamma radiation, including DNA damage and mutation induction
	– Inhibition of cell division and growth
Neutron radiation	– Changes in plant morphology and architecture
	– Induction of mutations and alterations in genetic material
	– Potential changes in plant physiology and metabolism
	– Variable effects on different crop species
	– Monitoring is required due to potential soil activation

(Source: Ahmar et al., [2023](#); Gao et al., [2023](#); Jiang et al., [2024](#); Maushe et al., [2023](#); Meshram et al., [2022](#); Singh et al., [2021](#); Sonkar et al., [2023](#))

plants and the nutritional value they possess. Plants have complex stress-responsive pathways triggered by different environmental stressors, such as radiation. The upregulation of stress-responsive genes, including those responsible for antioxidant enzymes and proteins involved in DNA repair, is triggered to alleviate the consequences of radiation-induced harm (Ali et al., [2022](#); Egea et al., [2022](#); Ganapathy et al., [2021](#); Imran & Ghosh, [2024](#); Manzanares et al., [2016](#); Mushtaq et al., [2018](#); Turan Büyükdinç et al., [2022](#)). Gaining comprehension of these pathways is essential for deciphering the molecular mechanisms of plant reactions to radiation stress. The main molecular consequence of radiation on crops is the initiation of DNA harm. Ionising radiation can directly or indirectly induce disruptions in the DNA double helix, forming lesions and mutations. Plants have developed sophisticated DNA repair mechanisms, such as base excision repair and homologous recombination, to minimise the effects of damage caused by radiation. Exposure to radiation causes stress in plant cells, producing reactive oxygen species (ROS). These reactive oxygen species (ROS) can potentially induce oxidative harm to various cellular constituents, such as lipids, proteins and nucleic acids. Plants employ antioxidant

defences, such as superoxide dismutase, catalase and peroxidases, to counteract oxidative stress. These enzymes remove reactive oxygen species (ROS) and safeguard cellular structures against oxidative harm. Radiation exposure can alter plant hormone levels, affecting plant growth, development and response to plant stress. One instance is the upregulation of abscisic acid (ABA), a hormone that responds to stress caused by radiation (Afzal et al., 2020; Bhatnagar-Mathur et al., 2015; Chengqi et al., 2023; Deoli & Hasenstein, 2018; Jaradat, 2016; Khah et al., 2024; Liu et al., 2023; Shohael & Hefferon, 2023; Zhao et al., 2022). This upregulation can activate adaptive responses, including stomata closure and increased stress tolerance. Understanding the molecular mechanisms underlying radiation-induced stress is crucial for devising approaches to bolster crop resilience and minimise potential adverse effects. The impact of radiation on crops can arise from both natural and human-caused sources, influencing how plants adapt to environmental challenges. During their growth, crops are exposed to radiation from natural sources such as cosmic radiation and terrestrial radioactivity. Human activities, such as nuclear power generation and medical and industrial applications, bring additional complexities and challenges to the agricultural environment. The morphological and physiological reactions of crops to stress caused by radiation are diverse and complex. These include inhibited growth, abnormalities in reproductive structures, disturbances in photosynthesis, changes in nutrient absorption and the initiation of stress-responsive pathways. Radiation-induced molecular stress causes DNA damage, triggers repair mechanisms, stimulates antioxidant defences and regulates hormone levels. Deciphering these complex molecular processes is essential for comprehending how plants overcome the difficulties posed by radiation exposure. Given the global challenges agriculture faces, such as climate change and the necessity for sustainable practices, it is becoming increasingly crucial to have a detailed understanding of the effects of radiation on crops. Employing strategies that exploit the beneficial effects of radiation, such as hormesis, while simultaneously reducing the risk of harm can aid in cultivating robust crop varieties. Furthermore, addressing the safety concerns related to human-made radiation sources is crucial to protect agricultural productivity and ensure food safety. We will first examine the impact of radiation on crops and then investigate the importance of stress-induced mutagenesis as a mechanism for plants to adapt and respond to environmental challenges and changing conditions (Ali et al., 2022; Biswal et al., 2019; Ganapathy et al., 2021; Khatri et al., 2023; Manzanares et al., 2016; Molitorisová et al., 2024; Muha-Ud-Din et al., 2024; Smith et al., 2023; Turan Büyükdinç et al., 2022; Zhang et al., 2023).

7.4 Impact of Radiation on Plant Physiology

The effects of radiation on plant physiology are complex, involving changes in plant structure and function. The growth and development of plants can be affected by radiation from both natural and human activities. This can result in changes in the physical structure of plants that are visible to the naked eye, as well as complex

molecular responses at the cellular level. This investigation aims to understand the intricate relationship between radiation and plant physiology. It seeks to elucidate the observable changes in plant structure and the physiological mechanisms that control these responses. A prominent morphological alteration caused by radiation is the inhibition of plant growth. This phenomenon becomes especially apparent when crops are subjected to elevated levels of ionising radiation. The growth impact is ascribed to the disturbance of cell division and elongation processes, specifically in the meristematic tissues accountable for primary growth (Fig. 7.4).

Impeded growth can affect plant development, impacting the total mass and the plant's capacity to vie for sunlight and nutrients. Gaining insight into the mechanisms that cause growth inhibition due to radiation is crucial for evaluating its impact on crop productivity. Radiation exposure can cause stress in plants, which can result in abnormalities in the development of their reproductive structures (Ahmar et al., 2023; Chengqi et al., 2023; Jaradat, 2016; Maushe et al., 2023; Meshram et al., 2022; Sharma et al., 2021; Suparmaniam et al., 2024). Flowers, essential for pollination and the subsequent production of seeds, can display abnormalities in their development. These abnormalities encompass a spectrum of variations, including modifications in the dimensions and form of flowers and changes in the quantity and pattern of floral structures. The effect on reproductive organs directly influences crop productivity, as successful pollination and seed formation are crucial for plant reproduction. Studying the precise impacts of radiation on reproductive organs offers a valuable understanding of potential repercussions for agricultural output. Photosynthesis is a fundamental process in plant physiology where plants convert light energy into chemical energy. The stress caused by radiation can disturb different components of photosynthetic machinery, leading to a decrease in energy conversion and nutrient assimilation efficiency. Radiation stress can induce alterations in chlorophyll content, which is the crucial green pigment

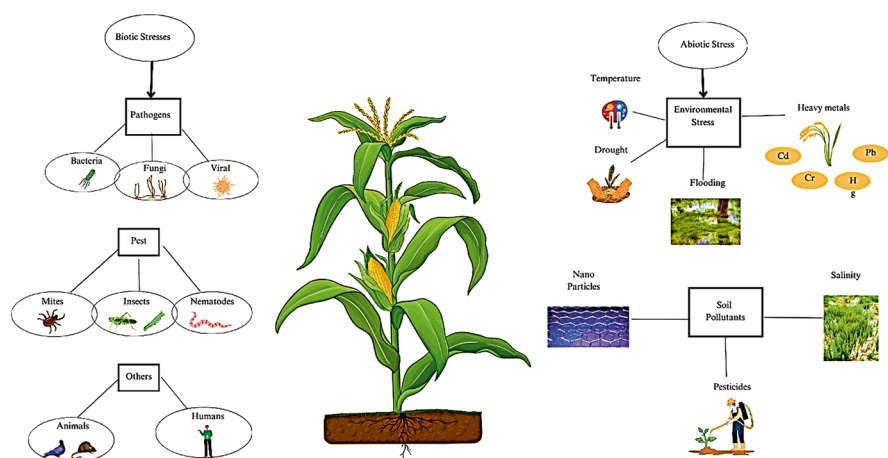


Fig. 7.4 Abiotic and biotic stress in plants

responsible for light absorption during photosynthesis. Decreases in chlorophyll concentrations can undermine the plant's capacity to capture sunlight and transform it into chemical energy. Observing changes in chlorophyll levels offers valuable information about how radiation affects the efficiency of photosynthesis. In addition to chlorophyll, radiation stress can affect the quantities and makeup of other photosynthetic pigments, such as carotenoids. These pigments have essential functions in the absorption of light and protection against its harmful effects. Fluctuations in their population can indicate the plant's adaptive reactions to stress caused by radiation. Photosynthesis entails an intricate network of enzymes facilitating crucial carbon fixation reactions and energy conversion. The enzymes' activity and expression can be influenced by stress caused by radiation. Studying the impact of radiation on photosynthetic enzymes offers valuable insights into the physiological adaptations of plants to deal with stress. Radiation exposure can cause plant stress, affecting their ability to absorb and use important nutrients. Radiation exposure can alter the plant's ion transport mechanisms, nutrient absorption and translocation. Disruption of nutrient uptake can result in imbalances of nutrient levels in plant tissues (Biswal et al., 2019; Egea et al., 2022; Khatri et al., 2023; Manzanares et al., 2016; Molitorisová et al., 2024; Muha-Ud-Din et al., 2024; Schröder et al., 2019; Smith et al., 2023). Consequently, this can impact diverse physiological mechanisms, such as enzyme function, osmotic regulation and overall plant metabolism. Evaluating the nutrient dynamics in plants exposed to radiation yields a thorough comprehension of the physiological ramifications of stress. Radiation stress can impact the accessibility and absorption of essential micronutrients, such as iron, zinc and copper. These micronutrients are indispensable for many biochemical processes and fulfil crucial functions in maintaining plant health. Studying the effects of radiation on the absorption of micronutrients enhances our comprehension of the complex connections between stress reactions and nutrient processing. Plants have complex stress-responsive pathways triggered when exposed to different environmental stressors, such as radiation. These pathways activate particular genes and produce proteins that enhance stress tolerance and adaptive responses (Chengqi et al., 2023; Deoli & Hasenstein, 2018; Gao et al., 2023; Jaradat, 2016; Shohael & Hefferon, 2023; Sivasankar et al., 2021; Suparmaniam et al., 2024; Ul Haq et al., 2022). Plants adjust the expression of stress-responsive genes as a reaction to stress caused by radiation. These genes contain the instructions for producing proteins involved in antioxidant defence, DNA repair and signal transduction. Studying alterations in gene expression allows us to understand the specific ways plants adapt to radiation stress at a molecular level. Radiation stress commonly leads to the production of reactive oxygen species (ROS). Plants initiate antioxidant defence mechanisms by activating enzymes like superoxide dismutase, catalase and peroxidases to reduce oxidative damage caused by reactive oxygen species (ROS). Evaluating the enzymatic activity provides insight into the plant's ability to mitigate oxidative stress caused by radiation. Radiation exposure can alter the concentrations of plant hormones, thereby affecting the processes of growth, development and responses to stress. Hormones such as abscisic acid (ABA), jasmonic acid (JA) and salicylic acid (SA) are essential for regulating plant responses to environmental stressors. Gaining

knowledge about hormonal regulation in response to radiation offers valuable insights into how plants integrate physiological signals to coordinate adaptive responses. Acquiring this knowledge is crucial for formulating tactics to augment plant resistance to stress caused by radiation (Biswal et al., 2019; Devos et al., 2024; Egea et al., 2022; Ganapathy et al., 2021; Khatri et al., 2023; Mushtaq et al., 2018). The influence of radiation on plant physiology involves a range of structural alterations and physiological reactions that collectively determine plants' adaptive tactics in reaction to environmental stressors. The effects of radiation-induced stress can be observed through stunted growth and abnormalities in reproductive structures, which significantly impact plants' overall development and ability to reproduce successfully. Physiological disturbances such as photosynthesis changes, nutrient absorption modifications and the initiation of stress-responsive pathways demonstrate plants' complex mechanisms to deal with radiation stress. The interaction of these physiological responses demonstrates the plant's ability to adapt and regulate essential processes to survive in difficult environmental conditions. As scientific research progresses, we will gain a more thorough understanding of the intricate molecular and physiological aspects of how radiation affects plant physiology. This knowledge has important implications for agriculture, as it offers insights into strategies for cultivating crops that have increased resistance to radiation stress and other environmental challenges. Understanding the intricate dynamics between radiation and plants enhances our capacity to utilise the beneficial aspects of radiation while mitigating potential risks and promoting sustainable agricultural methods in a constantly evolving world.

7.5 Molecular Mechanisms of Radiation-Induced Stress

The molecular mechanisms governing radiation-induced stress in plants are intricate and multifaceted, involving complex interactions at the cellular and genetic levels. Two key processes play pivotal roles in the plant's response to radiation stress: DNA damage and repair and the activation of stress-responsive pathways. Understanding these molecular mechanisms is essential for elucidating how plants cope with the challenges posed by radiation exposure and orchestrating adaptive responses to ensure survival and resilience. Ionising radiation, a common component of radiation stress, can directly or indirectly cause damage to the DNA molecules within plant cells. Direct damage involves ionising atoms within the DNA molecule, leading to DNA lesions such as single-strand breaks (SSBs) and double-strand breaks (DSBs). Indirect damage occurs when radiation interacts with cellular components, generating reactive oxygen species (ROS) that, in turn, induce oxidative DNA damage (Chengqi et al., 2023; Deoli & Hasenstein, 2018; Enders & Begcy, 2021; Jiang et al., 2024; Meshram et al., 2022; Sharma et al., 2021; Singh et al., 2021; Sivasankar et al., 2021). Plants have evolved intricate DNA repair mechanisms to counteract the harmful effects of radiation-induced DNA damage. BER is a critical mechanism for repairing small, non-helix-distorting lesions,

including ROS-induced oxidative damage. In this pathway, damaged bases are excised, and the gap is filled by DNA polymerases, followed by ligation to restore the integrity of the DNA strand. NER is primarily responsible for removing larger DNA lesions that distort the helical structure, such as those induced by UV radiation. This pathway involves excision a stretch of nucleotides containing the damaged site, followed by resynthesis and ligation (Fig. 7.5).

HR is a high-fidelity repair pathway that operates during the S and G2 phases of the cell cycle. It involves using an undamaged sister chromatid as a template for repair, ensuring accurate restoration of the damaged DNA sequence. NHEJ is an error-prone repair mechanism that rejoins broken DNA ends directly, often resulting in small insertions or deletions. This pathway is active throughout the cell cycle but is particularly prominent during the G1 phase (Ali et al., 2022; Egea et al., 2022; Khatri et al., 2023; Manzanares et al., 2016; Molitorisová et al., 2024; Schröder et al., 2019; Smith et al., 2023; Turan Büyükdinç et al., 2022; Zhang et al., 2023). Understanding the interplay between these repair pathways is crucial for deciphering the plant's ability to rectify radiation-induced DNA damage and maintain genomic integrity. Ionising radiation-induced stress generates reactive oxygen species (ROS) within plant cells. ROS, including superoxide radicals ($O_2^{\bullet-}$), hydrogen peroxide (H_2O_2) and hydroxyl radicals ($\bullet OH$), can cause oxidative damage to cellular components, including lipids, proteins and nucleic acids. In response, plants activate antioxidant defence mechanisms to neutralise ROS and mitigate oxidative stress. SOD catalyses the dismutation of superoxide radicals into hydrogen peroxide and oxygen. This enzyme is a frontline defender against ROS, preventing the accumulation of superoxide radicals within cells. CAT and peroxidases play crucial roles in scavenging hydrogen peroxide. CAT specifically catalyses the decomposition of hydrogen peroxide into water and oxygen, while peroxidases utilise reducing equivalents to reduce hydrogen peroxide and protect cells from oxidative damage. Plant hormones play pivotal roles in coordinating responses to radiation-induced stress. Hormones such as abscisic acid (ABA), jasmonic acid (JA) and salicylic acid (SA) are critical regulators of stress-responsive pathways. ABA is known for mediating abiotic stress responses, including those induced by radiation stress. ABA regulates stomatal closure, reducing water loss and enhancing drought tolerance. Additionally, ABA signalling can modulate antioxidant defences and influence the expression of stress-responsive genes. JA and SA regulate defence responses against biotic stresses but also play roles in abiotic stress responses, including radiation stress (Chengqi et al., 2023; Deoli & Hasenstein, 2018; Enders & Begcy, 2021; Goyal et al., 2023; Maushe et al., 2023; Meshram et al., 2022; Shohael & Hefferon, 2023; Singh et al., 2021; Sivasankar et al., 2021; Sonkar et al., 2023). These hormones can activate pathways that induce the expression of defence-related genes and enhance the plant's ability to cope with environmental challenges. Mitogen-activated protein kinases (MAPKs) are central components of signal transduction pathways that mediate stress responses in plants. Radiation-induced stress can activate MAPK cascades, phosphorylating downstream targets involved in stress signalling and response. MAPKs are activated through phosphorylation events involving three-tiered cascades of MAPK kinase (MAP3Ks), MAPK kinases

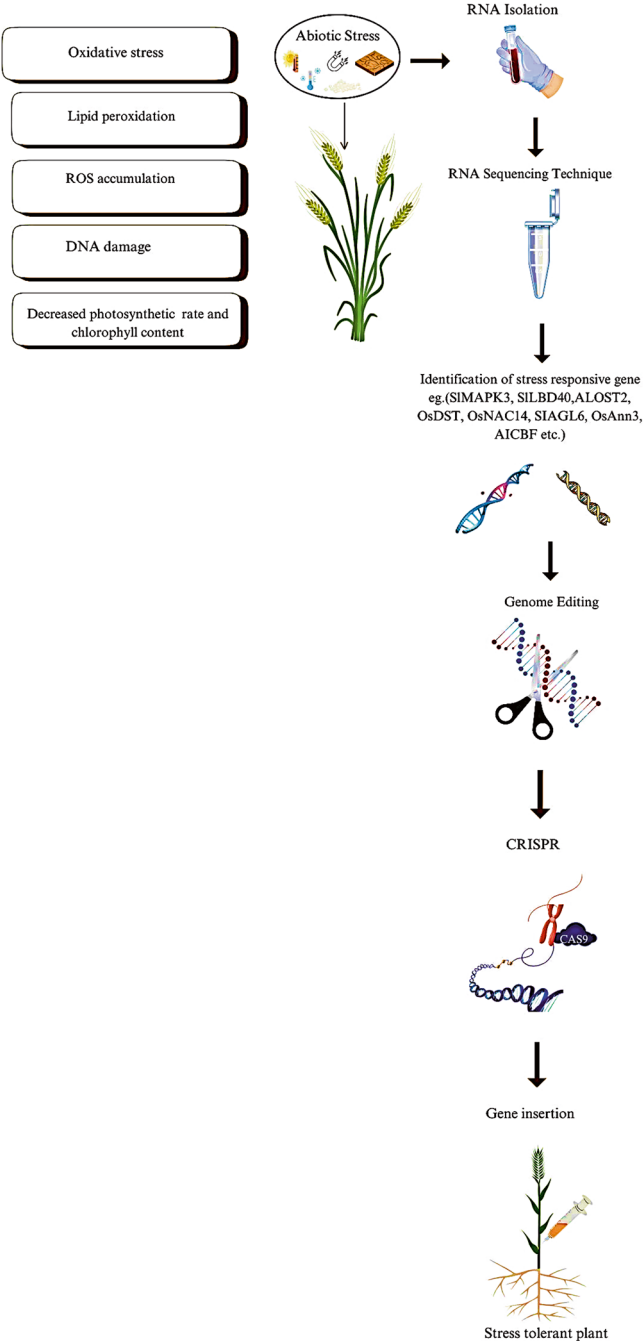


Fig. 7.5 Molecular mechanisms of radiation-induced stress. (Source: Created by authors)

(MAP2Ks) and MAPKs. These cascades transmit signals from the cell membrane to the nucleus, modulating gene expression and cellular responses to stress. Activated MAPKs can phosphorylate and activate transcription factors that regulate the expression of stress-responsive genes (Ali et al., 2022; Imran & Ghosh, 2024; Khatri et al., 2023; Manzanares et al., 2016; Molitorisová et al., 2024; Muha-Ud-Din et al., 2024; Smith et al., 2023; Turan Büyükdinç et al., 2022). These transcription factors bind to specific DNA sequences in the promoters of target genes, initiating the transcriptional reprogramming necessary for stress adaptation. The recognition and signalling of DNA damage are critical aspects of the plant's response to radiation-induced stress. DNA damage sensors and transducers transmit signals that activate downstream effectors, coordinating cellular responses to maintain genome integrity. Ataxia-telangiectasia mutated (ATM) and ATM- and Rad3-related (ATR) kinases are critical in DNA damage signalling pathways. They phosphorylate downstream targets involved in cell cycle checkpoint control, DNA repair and apoptosis, depending on the severity and nature of the DNA damage. ATM and ATR activation initiates cell cycle checkpoints, allowing the cell to pause and repair DNA damage before progressing through the cell cycle. Checkpoint activation ensures the fidelity of DNA repair and prevents the propagation of damaged DNA. The molecular mechanisms of radiation-induced plant stress involve a sophisticated interplay between DNA damage and repair mechanisms and the activation of stress-responsive pathways. As plants face the challenges imposed by ionising radiation, intricate cellular processes come into play to maintain genomic integrity, mitigate oxidative stress and orchestrate adaptive responses. Understanding these molecular mechanisms is essential for unravelling the plant's ability to navigate radiation-induced stress and developing strategies to enhance crop resilience (Chengqi et al., 2023; Deoli & Hasenstein, 2018; Maushe et al., 2023; Meshram et al., 2022; Peñas et al., 2023; Sharma et al., 2021; Shohael & Hefferon, 2023; Singh et al., 2021; Zhao et al., 2022). The interconnection between DNA damage repair, antioxidant defences, hormonal regulation and signalling pathways provides a comprehensive view of the plant's molecular arsenal against radiation stress. Future research in this field holds promise for uncovering additional components of these molecular networks, refining our understanding of the crosstalk between pathways and identifying potential targets for genetic manipulation to enhance plant resilience. Ultimately, deciphering the molecular intricacies of radiation-induced stress in plants contributes to fundamental knowledge in plant biology and the development of innovative approaches for sustainable agriculture in the face of environmental challenges.

7.6 Stress-Induced Mutagenesis in Agricultural Crops

Stress-induced mutagenesis is an intriguing occurrence in plant biology, as it allows crops to produce genetic variation in reaction to environmental stressors. This process, propelled by diverse stressors, assumes a pivotal function in the adjustment

and progression of plant populations. Regarding crops, it is crucial to comprehend stress-induced mutagenesis to create robust varieties that endure various environmental conditions. This investigation examines the specific factors that cause genetic mutations, with a particular emphasis on environmental and biological pressures and their effects on the ability of crops to adapt. Temperature variations, including high and low extremes, are important environmental factors that can cause significant ecological stress and lead to genetic changes in crops, known as mutagenesis. Temperature stress impacts multiple facets of plant physiology, including DNA replication and repair mechanisms. Temperature stress-induced mutations can contribute to the generation of genetic diversity, potentially resulting in the emergence of crop varieties that are tolerant to high temperatures (Biswal et al., 2019; Egea et al., 2022; Kumar et al., 2021; Manzanares et al., 2016; Molitorisová et al., 2024; Muha-Ud-Din et al., 2024; Smith et al., 2023; Zhang et al., 2023). Water scarcity, a widespread environmental pressure, triggers adaptive plant reactions, such as stress-induced mutagenesis. Drought stress modifies cellular processes, impacting the stability of DNA and the mechanisms involved in its repair. Plants experiencing water stress may undergo genetic alterations that enhance their ability to withstand long periods of drought, ultimately leading to improved water-use efficiency in crops. Elevated levels of soil salinity greatly hinder agricultural productivity. The presence of high levels of salt causes genetic mutations in crops by disrupting the integrity of DNA and interfering with the pathways responsible for DNA repair. Plants exposed to salt stress may experience genetic mutations that result in the development of salt tolerance, which is an essential characteristic for crops grown in saline environments or irrigated with salty water. Ultraviolet (UV) radiation is a powerful environmental factor that can cause genetic mutations in crops by affecting their DNA. UV-induced mutagenesis is a process that allows plants to adapt to changes in solar radiation. Comprehending the genetic alterations induced by UV radiation is crucial for advancing crops with improved UV tolerance, especially in areas with significant UV exposure. Pathogen attacks, such as those caused by bacteria, fungi, viruses and other pathogens, are major biotic stressors that trigger crop mutagenesis. The reciprocal adaptation process between plants and pathogens leads to the development of genetic diversity through mutagenesis. Plants can undergo deliberate mutations to acquire resistance against particular pathogens, which serves as a flexible defence strategy. Crop mutagenesis can be triggered by herbivore infestations, which introduce distinct biotic stresses. The interaction between plants and herbivores triggers the activation of defence mechanisms, such as stress-induced mutagenesis. Plants can experience genetic alterations that provide resistance or discourage herbivores, thereby contributing to improved pest resistance in crops (Ahmar et al., 2023; Deoli & Hasenstein, 2018; Goyal et al., 2023; Jaradat, 2016; Jiang et al., 2024; Maushe et al., 2023; Meshram et al., 2022; Sharma et al., 2021; Zhao et al., 2022). Interplant competition for resources, such as nutrients and light, can cause stress and mutagenesis. Plants can experience mutagenesis in densely populated agricultural environments, where crops are closely planted to enhance their ability to compete for vital resources. Gaining insight into the genetic adaptations influenced by resource competition is essential for maximising crop

productivity in high-density planting situations. Stress-induced mutagenesis frequently entails the utilisation of error-prone DNA repair mechanisms, which introduce mutations while carrying out the repair process. Although DNA repair mechanisms typically strive to restore the original DNA sequence faithfully, stress conditions can trigger alternative repair pathways prioritising speed over accuracy. Pathways prone to errors, such as translesion synthesis, play a role in causing mutations in the repaired DNA. The SOS response is a thoroughly studied mechanism in bacteria, and similar mechanisms have been found in plants. The SOS response is initiated in response to DNA damage and activates a group of genes responsible for DNA repair and mutagenesis. Under stressful conditions, plants may activate SOS-like responses, facilitating stress-induced mutagenesis. This process enables plants to adapt to dynamic environments quickly. Plant cells frequently produce reactive oxygen species (ROS) due to environmental and biotic stresses. Reactive oxygen species (ROS), such as singlet oxygen, superoxide radicals and hydrogen peroxide, can induce oxidative DNA damage. Oxidative DNA damage repair may involve error-prone repair pathways, which can contribute to stress-induced mutagenesis. Plants can trigger particular enzymes with mutagenic properties when exposed to stressful conditions (Devos et al., 2024; Egea et al., 2022; Ganapathy et al., 2021; Hossain et al., 2021; Khatri et al., 2023; Molitorisová et al., 2024; Mushtaq et al., 2018; Smith et al., 2023). For instance, when stress triggers the activation of DNA glycosylases, which are enzymes responsible for base excision repair, they can eliminate damaged bases, causing mutations during the repair synthesis process. Stress-induced mutagenesis amplifies genetic diversity among plant populations. Introducing genetic variations expands the potential range of observable traits, thereby enhancing the likelihood of identifying individuals with enhanced stress tolerance. Utilising the genetic variability produced by mutagenesis is essential for crop breeding initiatives focused on creating robust varieties that can effectively adjust to evolving environmental circumstances. Stress-induced mutagenesis expedites the process of genetic diversity generation, thereby hastening evolutionary responses in plant populations (Ahmar et al., 2023; Deoli & Hasenstein, 2018; Jaradat, 2016; Maushe et al., 2023; Shohael & Hefferon, 2023; Sivasankar et al., 2021; Sonkar et al., 2023). The adaptive mechanism allows crops to effectively respond to evolving environmental challenges, including climate variations, emerging pathogens and increasing herbivore populations. Gaining a comprehensive understanding of the mechanisms behind stress-induced mutagenesis offers valuable insights into the capacity of crops to adapt and thrive. Understanding stress-induced mutagenesis provides opportunities for implementing focused breeding techniques in agriculture. Breeders can deliberately subject crops to controlled stress conditions to trigger targeted genetic alterations that may result in advantageous characteristics, such as heightened stress resilience, disease resistance or increased resource utilisation efficiency. Stress-induced mutagenesis can enhance conventional breeding methods, facilitating targeted and expedited crop enhancement. Although stress-induced mutagenesis provides prospects for enhancing crops, it poses challenges and ethical concerns. The uncertainty of mutagenesis results and the possibility of unintentional genetic alterations give rise to apprehensions

regarding the safety and regulatory dimensions of crops produced using this technique. Achieving a harmonious equilibrium between utilising the advantages of stress-induced mutagenesis and addressing ethical and safety concerns is crucial for crops' responsible and enduring enhancement (Ali et al., 2022; Egea et al., 2022; Ganapathy et al., 2021; Hossain et al., 2021; Imran & Ghosh, 2024; Manzanares et al., 2016; Muha-Ud-Din et al., 2024; Smith et al., 2023; Turan Büyükdiñç et al., 2022). Crop stress-induced mutagenesis responds and adapts to environmental and biotic challenges. The interaction among stressors, DNA damage and repair mechanisms and the activation of stress-responsive pathways produces genetic variation, influencing the ability of crops to adapt. Gaining insight into the molecular mechanisms and consequences of stress-induced mutagenesis is crucial for advancing crops that can flourish in response to changing environmental circumstances. Given the challenges posed by climate change, emerging diseases and changing pest pressures, it is becoming increasingly crucial to utilise stress-induced mutagenesis to tap into the adaptive capabilities of agricultural systems. Incorporating this knowledge into breeding programmes, alongside ethical considerations and safety precautions, shows potential for creating robust crop varieties that enhance global food security in a swiftly evolving world.

7.7 Mechanisms of Stress-Induced Mutagenesis

Stress-induced mutagenesis is an intriguing occurrence in plant biology, which serves as an adaptive reaction to environmental difficulties. The molecular processes involved in stress-induced mutagenesis are complex and include DNA repair mechanisms that can introduce mutations and activate mutagenic enzymes. Comprehending these mechanisms is essential for unravelling how plants produce genetic variation in reaction to stress and how this variation contributes to adaptation and evolution. Plants employ DNA repair mechanisms to correct damage caused by environmental stressors under stressful conditions. While certain repair pathways strive to restore the original DNA sequence accurately, stress-induced mutagenesis frequently involves DNA repair mechanisms prone to errors. These pathways prioritise expedient restoration over precision, resulting in the occurrence of mutations during the repair process (Afzal et al., 2020; Ali et al., 2022; Chengqi et al., 2023; Egea et al., 2022; Jaradat, 2016; Khah et al., 2024; Schröder et al., 2019; Singh et al., 2024; Sivasankar et al., 2021; Smith et al., 2023; Turan Büyükdiñç et al., 2022; Zhang et al., 2023). Translesion synthesis is a well-known DNA repair pathway that is prone to errors. It is activated when regular repair mechanisms come across lesions or damage in the DNA template. Translesion synthesis (TLS) entails enlisting specialised polymerases capable of replicating through damaged DNA, thereby enabling the uninterrupted progression of DNA synthesis in the presence of lesions. The polymerases involved in translesion synthesis (TLS) exhibit a lenient fidelity, rendering them susceptible to the introduction of mutations. Mismatch repair is a universally preserved repair pathway that is responsible for rectifying

mistakes that occur during the process of DNA replication. During periods of stress, the DNA repair mechanism known as mismatch repair (MMR) can exhibit a higher likelihood of errors, resulting in occurrences called slippage events. These events involve adding or deleting short DNA sequences during the repair process. This leads to minor insertions or deletions (indels) and contributes to the overall genetic diversity. Severe stress causes DNA double-strand breaks (DSBs) to occur, which are then repaired using pathways such as non-homologous end joining (NHEJ) and homologous recombination (HR). Non-homologous end joining (NHEJ) is a repair mechanism that directly reconnects broken DNA ends, frequently resulting in mutations at the repair site. HR, or homologous recombination, enhances fidelity and promotes genetic diversity by exchanging genetic material between homologous chromosomes. Plants, akin to bacteria, can trigger SOS-like reactions when faced with stressful circumstances. The SOS response is a universally preserved mechanism that synchronises the processes of DNA repair and mutagenesis. Inducing SOS-like reactions in plants may entail the increased expression of particular genes linked to error-prone DNA repair, which aids in introducing mutations as a stress response component. Stress-induced mutagenesis is linked to the production of reactive oxygen species (ROS), which are produced due to different stress conditions. Reactive oxygen species (ROS) can induce oxidative damage to DNA, forming lesions such as 8-oxo guanine. The process of repairing oxidative DNA damage involves specific pathways that have the potential to introduce mutations during the synthesis of repairs. This can contribute to the occurrence of mutagenesis caused by stress. DNA glycosylases are enzymes in the base excision repair process, eliminating damaged or incorrect DNA bases. When subjected to stressful conditions, plants may trigger particular DNA glycosylases with mutagenic properties. These enzymes can identify and remove damaged bases, resulting in the formation of apurinic or apyrimidinic sites. These sites, when repaired, have the potential to cause mutations. APOBEC deaminases are recognised for their DNA and RNA editing involvement, also known as apolipoprotein B mRNA-editing enzymes and catalytic polypeptide-like deaminases. Certain members of the APOBEC family can catalyse the deamination of cytosine, resulting in the formation of uracil and causing mismatches in the DNA sequence. These discrepancies can trigger genetic alterations during the repair process, thereby contributing to the occurrence of mutations caused by stress. ROS produced under stressful conditions can stimulate oxidative enzymes that contribute to the occurrence of mutations. One instance is the enzyme DNA-dependent RNA polymerase (RDR), which plays a role in plant mutagenesis caused by reactive oxygen species (ROS). RDR catalyses the synthesis of RNA using a single-stranded DNA template while inducing mutations in the genetic material. RNA-mediated mutagenesis is a distinct mechanism contributing to genetic diversity in response to stress. During periods of stress, the activation of reverse transcriptases and enzymes that synthesise complementary DNA (cDNA) from RNA templates can contribute to the occurrence of mutations caused by stress. The process, referred to as retrotranscription, can result in the incorporation of cDNA copies into the plant genome, which has the potential to introduce mutations and enhance genetic diversity. Stress-induced mutagenesis mechanisms offer plants

an effective means to generate genetic diversity quickly. The presence of diverse genetic variations provides a reservoir of advantageous characteristics that can aid in adapting crops to dynamic and demanding environments. Stress-induced mutagenesis can be pivotal in cultivating crop varieties with enhanced stress tolerance and resilience. Stress-induced mutagenesis plays a role in the rapid evolutionary adaptations of plant populations. The production of genetic variation enables natural selection to operate on a wider range of characteristics, favouring individuals with genetic alterations that enhance their ability to survive in stressful environments. The interaction between mutagenesis and natural selection is responsible for the adaptation and evolution of plant populations in response to environmental challenges. Although stress-induced mutagenesis presents opportunities for enhancing crops, it also presents challenges and ethical concerns. The inherent unpredictability of mutagenesis outcomes, which may result in the accidental introduction of unintended genetic alterations, raises safety concerns. To tackle these challenges, adopting a well-rounded strategy that includes thorough safety evaluations, regulatory structures and ethical deliberations is necessary when employing stress-induced mutagenesis for crop improvement. A complex interaction between error-prone DNA repair pathways and the activation of mutagenic enzymes drives stress-induced mutagenesis in plants. The environmental and biotic stressors stimulate molecular processes that lead to the rapid creation of genetic diversity in plant populations. A comprehensive understanding of the complex details of stress-induced mutagenesis is crucial for effectively utilising its potential in enhancing crops. This knowledge enables the development of resilient plant varieties that thrive in a wide range of challenging and ever-changing agricultural environments. As research progresses, incorporating information on stress-induced mutagenesis into crop breeding programmes shows potential for improving global food security and sustainability in response to changing environmental challenges.

7.8 Role of Stress-Induced Mutagenesis in Crop Adaptation

Stress-induced mutagenesis is crucial for crops to respond dynamically and adaptively to environmental challenges. The occurrence of different stressors triggers this process, resulting in the emergence of genetic diversity within crop populations. The resulting diversity functions as a reservoir of potential traits that can aid in the adaptation of crops to dynamic and challenging environments. This study investigates the influence of stress-induced mutagenesis on crop adaptation, specifically examining its effects on genetic diversity and the evolutionary consequences for agricultural systems. Stress-induced mutagenesis is crucial in crop adaptation by quickly creating genetic diversity among plant populations (Aggarwal et al., 2024; Ali et al., 2022; Biswal et al., 2019; Ganapathy et al., 2021; Imran & Ghosh, 2024; Turan Büyükdinç et al., 2022). Stress responses lead to the emergence of mutations, resulting in a wide range of genetic variations. These variations include modifications in nucleotide sequences, rearrangements of chromosomes and changes in gene

expression. This variety of organisms serves as the foundation for natural selection, which allows for identifying and favouring individuals possessing beneficial characteristics in response to particular environmental pressures. Stress-induced mutagenesis generates genetic diversity, which enhances the potential for stress tolerance in crop populations. Individuals possessing genetic mutations that enhance their ability to withstand adverse environmental conditions, such as drought, salinity or pathogen assaults, have a higher probability of survival and reproductive success. Over time, the frequency of stress-tolerant characteristics among individuals in the population rises, thereby augmenting the overall ability of crops to withstand difficult environmental conditions. Stress-induced mutagenesis enables the investigation and development of new characteristics that may be absent in the initial crop population. Introducing mutations can result in the manifestation of hidden genetic diversity or the formation of completely novel genetic configurations. The ability to investigate new characteristics is invaluable in uncertain and swiftly evolving environmental circumstances, where the adaptability of crops is crucial for the long-term viability of agriculture. The practical applications of stress-induced mutagenesis in crop breeding arise from the genetic diversity it generates (Afzal et al., 2020; Bhatnagar-Mathur et al., 2015; Chengqi et al., 2023; Deoli & Hasenstein, 2018; Enders & Begcy, 2021; Jiang et al., 2024; Khah et al., 2024; Marwein et al., 2019; Meshram et al., 2022; Shohael & Hefferon, 2023; Singh et al., 2024). Conventional breeding techniques frequently depend on identifying and cultivating naturally existing genetic variations. Stress-induced mutagenesis expedites this process by deliberately causing mutations, offering breeders a wider range of characteristics. Utilising the genetic variation produced by mutagenesis enables the creation of crop cultivars with enhanced agronomic traits, stress resistance and overall adaptability. Stress-induced mutagenesis plays a role in speeding up evolutionary adaptations in crop populations. Crops can adapt to changing environmental challenges quickly due to the rapid generation of genetic diversity. Rapid evolution is essential for crops' enduring viability and prosperity in light of climate change, emerging diseases and other sources of strain. The relationship between crops and their environment is influenced by the co-evolutionary dynamics that are shaped by mutagenesis induced by stress. Under the influence of changing environmental conditions, crops experience stress-induced mutagenesis, leading to the adaptation of pests, pathogens and other interacting organisms. The reciprocal interaction between crops and their biotic environment, known as co-evolution, plays a significant role in the ongoing competition between them. This process emphasises the significance of stress-induced mutagenesis in shaping the genetic makeup of crops and the organisms they are associated with. Stress-induced mutagenesis causes the introduction of a range of genetic variations into crop populations, exposing them to environmental selection pressures. The fitness of individuals with particular genetic characteristics is determined by their capacity to survive, reproduce and transmit these traits to future generations. The occurrence of genetic variations that enhance adaptability to stress conditions, resulting from stress-induced mutagenesis and subsequent natural selection, contributes to the evolutionary success of crop populations. Stress-induced mutagenesis promotes adaptive radiation, enabling crops to expand

into new ecological niches or adapt more efficiently to existing niches. Generating diverse genetic variants allows crops to adapt to environmental conditions and ecological niches. This phenomenon of adaptive radiation is especially significant in the context of worldwide agricultural systems, where a wide range of quickly shifting climates require crops to adapt to different agro-ecological conditions. Although stress-induced mutagenesis offers a means of generating genetic diversity, the results are inherently uncertain. The genetic alterations induced during stress responses can vary, and the resulting observable characteristics may not consistently correspond to the intended objectives of enhancing crops. Coping with and controlling this inherent unpredictability poses a significant challenge when employing stress-induced mutagenesis for crop adaptation (Biswal et al., 2019; Imran & Ghosh, 2024; Khatri et al., 2023; Leung & An, 2004; Molitorisová et al., 2024; Smith et al., 2023). Utilising stress-induced mutagenesis in crop breeding gives rise to ethical and safety concerns. Rigorous safety assessments are necessary to ensure the safety of crops and the environment due to the introduction of unpredictable mutations. It is crucial to consider the advantages of stress-induced mutagenesis while also considering ethical concerns and implementing safety measures to ensure responsible and sustainable crop enhancement. Stress-induced mutagenesis fundamentally influences crops' genetic diversity and adaptive capacity. Crops can quickly generate genetic variability, which enables them to develop new traits, improve their ability to withstand stress and experience faster evolutionary changes. The interaction among stress-induced mutagenesis, genetic diversity and evolutionary dynamics is crucial for the ability of crops to withstand and adapt to various and changing environmental challenges. Given the challenges posed by climate change, emerging diseases and changing global landscapes, it is crucial to comprehend and utilise the influence of stress-induced mutagenesis in crop adaptation within agriculture. Incorporating this knowledge into crop breeding programmes while addressing ethical and safety concerns shows potential for developing robust and versatile crop varieties that contribute to global food security in a rapidly evolving world.

7.9 Interplay Between Radiation and Stress-Induced Mutagenesis

The interplay between radiation and stress-induced mutagenesis represents a fascinating intersection in plant biology, with profound implications for crop adaptation and resilience. Both radiation and various environmental stresses can individually induce mutagenesis, but their combined effects create a dynamic landscape of genetic diversity within crop populations. This exploration delves into the synergistic effects of radiation and stress-induced mutagenesis on crop resilience, elucidating the molecular crosstalk between radiation and stress responses that underlies plants' adaptive strategies. The combined exposure to radiation and environmental

stresses leads to an amplification of genetic diversity within crop populations (Egea et al., 2022; Khatri et al., 2023; Kumar et al., 2021; Molitorisová et al., 2024; Muha-Ud-Din et al., 2024; Mushtaq et al., 2018; Smith et al., 2023). Radiation-induced mutagenesis, driven by ionising radiation's direct or indirect effects on DNA, interacts with stress-induced mutagenesis triggered by environmental challenges. This dual influence results in a broader spectrum of genetic variants, including point mutations, chromosomal rearrangements and epigenetic modifications. The amplification of genetic diversity enhances the potential for crop resilience, allowing for a more robust response to complex and dynamic agricultural environments. The synergy between radiation and stress-induced mutagenesis contributes to enhanced stress tolerance in crops. The simultaneous activation of mutagenic processes in response to radiation and environmental stresses allows plants to explore various genetic solutions for stress adaptation. The introduction of mutations that confer tolerance to radiation, as well as specific environmental stressors such as drought or salinity, enhances the overall resilience of crops. This enhanced stress tolerance is crucial for sustaining agricultural productivity in the face of multifaceted challenges. The interplay between radiation and stress-induced mutagenesis promotes adaptive plasticity in crop populations. Plants exposed to radiation and environmental stresses undergo dynamic changes in their genetic makeup, allowing for rapid adjustments to shifting environmental conditions. This adaptive plasticity enables crops to thrive in diverse agroecological contexts, responding dynamically to variations in climate, soil conditions and pest pressures. The plasticity generated through the interplay of radiation and stress-induced mutagenesis is a critical factor in crop resilience and adaptability. The synergistic effects of radiation and stress-induced mutagenesis facilitate accelerated evolutionary responses in crop populations. The combination of mutagenic processes creates a dynamic landscape for natural selection to act upon, favouring individuals with genetic traits that confer fitness under the combined stresses. This facilitation of evolutionary responses enables crops to adapt rapidly to changing climates, emerging diseases and other environmental challenges, contributing to agricultural systems' long-term survival and success. The molecular crosstalk between radiation and stress responses involves shared signalling pathways integrating signals from both stressors. One such pathway is the mitogen-activated protein kinase (MAPK) signalling cascade, which is central in transmitting signals from radiation-induced DNA damage and various environmental stresses. Activation of MAPKs initiates downstream responses, including the expression of stress-responsive genes and the modulation of DNA repair pathways. Reactive oxygen species (ROS) commonly mediate radiation and stress responses. Ionising radiation induces the generation of ROS directly within plant cells, while environmental stresses, such as drought or pathogen attacks, can also trigger ROS production (Ahmar et al., 2023; Chengqi et al., 2023; Jiang et al., 2024; Meshram et al., 2022; Singh et al., 2024; Sivasankar et al., 2021; Zhao et al., 2022). The shared involvement of ROS in radiation and stress-induced mutagenesis suggests an intricate network of signalling events. ROS-mediated signalling pathways can activate stress-responsive genes, influence DNA repair mechanisms and contribute to the induction of mutagenic processes. Radiation and environmental stresses activate

plants' DNA damage response (DDR) pathways. Recognition and repair of DNA damage are central components of the adaptive strategies employed by plants. In response to radiation-induced DNA damage and various environmental stressors, the activation of ATM (ataxia-telangiectasia mutated) and ATR (ATM- and Rad3-related) kinases, critical players in DDR pathways, is observed. These kinases coordinate cellular responses, including regulating cell cycle checkpoints and initiating DNA repair processes. Plant hormones are crucial in coordinating responses to radiation and environmental stresses. Hormones such as abscisic acid (ABA), jasmonic acid (JA) and salicylic acid (SA) are critical regulators of stress responses. They are involved in the crosstalk between radiation and stress-induced mutagenesis. Hormonal signalling pathways influence the expression of stress-responsive genes, modulate antioxidant defences and contribute to the overall adaptive responses of plants to combined stress scenarios. The crosstalk between radiation and stress responses involves cross-activating transcription factors regulating gene expression. Transcription factors, such as those in the AP2/ERF (APETALA2/ethylene-responsive element-binding factor) family, are implicated in the coordinated regulation of genes involved in radiation and stress responses. The cross-activation of these transcription factors contributes to the integration of molecular reactions, shaping the overall adaptive strategies of plants exposed to combined stressors. Epigenetic modifications regulate gene expression in response to radiation and environmental stresses. DNA methylation, histone modifications and small RNA-mediated silencing are epigenetic mechanisms involved in the crosstalk between radiation and stress-induced mutagenesis (Ahmar et al., 2023; Biswal et al., 2019; Chengqi et al., 2023; Egea et al., 2022; Jiang et al., 2024; Khatri et al., 2023; Meshram et al., 2022; Singh et al., 2024; Sivasankar et al., 2021; Smith et al., 2023; Zhang et al., 2023; Zhao et al., 2022). Epigenetic modifications can influence the stability of the plant genome, modulate gene expression patterns and contribute to the heritability of stress-induced traits. The interplay between radiation and stress-induced mutagenesis represents a complex and synergistic relationship that profoundly influences crop resilience and adaptation. The amplification of genetic diversity, enhanced stress tolerance, adaptive plasticity and facilitation of evolutionary responses highlight this interplay's significance in shaping crops' adaptive strategies. At the molecular level, shared signalling pathways, ROS-mediated signalling, activation of DDR pathways, hormonal regulation, cross-activation of transcription factors and epigenetic modifications underscore the intricate crosstalk between radiation and stress responses. Understanding the interplay between radiation and stress-induced mutagenesis provides insights into the integrated molecular mechanisms governing plant responses to complex environmental scenarios. This knowledge is essential for developing strategies to harness the synergistic effects of radiation and stress-induced mutagenesis in crop breeding programs. Ultimately, deciphering the molecular intricacies of this interplay contributes to fundamental knowledge in plant biology and the development of innovative approaches for sustainable agriculture in the face of evolving environmental challenges.

7.10 Applications for Enhancing Crop Resilience

Given the challenges of climate change, evolving pests and the need for sustainable practices, it is increasingly important to improve the ability of crops to withstand and recover from these difficulties. Two primary methods for accomplishing this objective are utilising radiation-induced effects and stress-induced mutagenesis in crop breeding. These approaches provide novel methods to create genetic variation, enhance stress resistance and aid in developing robust crop varieties. This exploration focuses on the practical uses of these techniques, analysing methods for utilising radiation-induced effects, employing stress-induced mutagenesis and outlining possibilities for sustainable agriculture. Ionising radiation, such as gamma rays or X-rays, has traditionally been employed as a mutagenic agent to provoke genetic variation in crops. Ionising radiation exposure causes DNA damage, which includes point mutations, chromosomal rearrangements and deletions. Seeds or plant tissues are exposed to carefully controlled doses of ionising radiation to harness radiation-induced mutagenesis, creating a varied population of mutants (Ahmar et al., 2023; Chengqi et al., 2023; Jiang et al., 2024; Meshram et al., 2022; Peñas et al., 2023; Sonkar et al., 2023; Zhao et al., 2022). These mutant organisms can be examined to identify favourable characteristics, such as increased ability to withstand stress, improved productivity or immunity against particular pathogens. In addition to mutagenesis, deliberate exposure to ionising radiation can trigger plant radio resistance. Pre-treating crops with small amounts of ionising radiation triggers stress-responsive pathways and DNA repair mechanisms, better-preparing plants to withstand subsequent, potentially harmful doses. This strategy can be advantageous for regions susceptible to radiation events or where exposure to specific stressors is unavoidable. Cultivating crops with artificially enhanced resistance to radiation helps to increase their ability to withstand environmental adversities. Identifying and utilising radiation-responsive genes can selectively breed crops with improved resilience. Investigating the molecular reactions of plants to ionising radiation uncovers essential genes implicated in stress signalling, DNA repair and antioxidative defences. By integrating these radiation-responsive genes into crop breeding programmes, researchers can create improved varieties that exhibit enhanced stress responses. This method enables the accurate adjustment of particular pathways to improve resilience without solely depending on random mutagenesis. Stress-induced mutagenesis is a method used to deliberately create genetic variation in crops by exposing them to carefully controlled environmental stresses, such as extreme temperatures, drought, salinity or pathogen attacks. This method utilises the inherent adaptive reactions of plants to stress by stimulating mutagenic mechanisms. Breeders can manipulate the genetic changes in crops by subjecting them to carefully controlled stress conditions at specific stages of development. Controlled stress exposure offers a focused and repeatable approach to creating genetic diversity. Stress-induced mutagenesis expedites breeding cycles by swiftly introducing genetic diversity into crop populations. Conventional breeding techniques frequently depend on gradually accumulating genetic variations via sexual

reproduction. Stress-induced mutagenesis accelerates this process by causing mutations within a single generation. This acceleration is especially beneficial when prompt reactions to emerging environmental challenges or shifting market demands are crucial. Marker-assisted selection (MAS) can integrate stress-induced mutations into breeding programmes (Ali et al., 2022; Devos et al., 2024; Imran & Ghosh, 2024; Khatri et al., 2023; Manzanares et al., 2016; Molitorisová et al., 2024; Schröder et al., 2019; Smith et al., 2023; Turan Büyükdinç et al., 2022). MAS enables breeders to pinpoint and choose plants with advantageous mutations without time-consuming phenotypic screening. Breeders can optimise the selection process by linking molecular markers to advantageous stress-induced characteristics, enabling them to concentrate on individuals exhibiting specific enhancements in stress resistance, crop yield or other agricultural traits. Progress in genomic technologies, such as next-generation sequencing, allows for a thorough comprehension of the mutational patterns caused by stress. Whole-genome sequencing and functional genomics methods offer valuable insights into the genetic alterations linked to stress-induced mutagenesis. Incorporating genomic data into crop breeding programmes enables more accurate and knowledgeable identification of individuals possessing favourable mutations, thereby enhancing the effectiveness of trait enhancement. Utilising the effects caused by radiation and the mutagenesis induced by stress shows great potential for developing resilient crop varieties to climate change. Crops must quickly adapt to new environmental conditions due to the unpredictable and fluctuating climate patterns. By implementing these mutagenic techniques, breeders can develop crops that possess improved resistance to variations in temperature, limited water availability and other stressors associated with climate change. Climate-resilient varieties enhance the sustainability of agriculture by guaranteeing consistent yields despite unpredictable climatic obstacles. Stress-induced mutagenesis is a useful technique for improving the ability of crops to resist diseases and tolerate pests. Breeders can induce mutations that provide resistance to prevalent diseases or pest pressures by exposing plants to stressors.

This approach applies to areas where emerging diseases or evolving pest populations threaten crop productivity. Creating cultivars with inherent resistance via stress-induced mutagenesis decreases the need for chemical interventions, aligning with sustainable and ecofriendly agricultural methods. Stress-induced mutagenesis can enhance crop resource utilisation efficiency, promoting sustainable agriculture (Afzal et al., 2020; Bhatnagar-Mathur et al., 2015; Enders & Begcy, 2021; Khah et al., 2024; Liu et al., 2023; Shahwar et al., 2023; Shohael & Hefferon, 2023). Breeders can enhance plant resource utilisation by subjecting them to stress conditions related to limited resources, such as nutrient deficiencies or competition for sunlight. Implementing this method is essential for enhancing crop productivity in agroecological settings with fluctuating resource availability and encouraging sustainable agricultural techniques with minimised inputs. Radiation-induced effects and stress-induced mutagenesis generate genetic diversity, which plays a role in conserving biodiversity within crop populations. Preserving a wide range of genetic resources is crucial for protecting against unexpected environmental threats and adapting to changing pathogens. Creating various crop varieties that can withstand

stress ensures that genetic resources are available for future breeding projects. The presence of diverse elements is crucial for ensuring the long-term viability of agriculture and its capacity to respond effectively to unforeseen shifts in the agricultural environment as mutagenic techniques in crop breeding progress and ethical and regulatory considerations become paramount. It is essential to prioritise the safety of newly created varieties, address potential unintended consequences and promote transparency in breeding practices to implement them responsibly. Practical cooperation among scientists, policymakers and the public is crucial to developing ethical guidelines and regulatory frameworks that balance the potential advantages of improved crop resilience and the need to address environmental and safety issues. Utilising radiation-induced effects and stress-induced mutagenesis in crop breeding presents novel approaches to improve crop resilience for sustainable agriculture. These methods offer strategies to effectively manage the challenges posed by shifting climates, emerging pests and limited resources. Scientists and breeders can enhance crops' stress tolerance, disease resistance and resource utilisation efficiency by harnessing the interaction between radiation and stress-induced mutagenesis. By incorporating these mutagenic strategies into breeding programmes, we can potentially guarantee food security and sustainability in an ever-changing world as the agricultural landscape progresses. Ensuring responsible implementation, considering ethical considerations and establishing regulatory frameworks are crucial for optimising the advantages of these approaches while mitigating potential risks.

7.11 Challenges and Future Directions

Scientists have encountered various obstacles and restrictions as they delve deeper into the possibilities of utilising radiation-induced effects and stress-induced mutagenesis in crop breeding. Tackling these challenges is essential for progressing our comprehension, guaranteeing ethical methodologies and unleashing the complete potential of these groundbreaking approaches. This investigation examines the constraints in the existing understanding, moral considerations and safety issues while outlining future research avenues and possible advancements in the field. A significant limitation in utilising radiation-induced effects and stress-induced mutagenesis is the inherent uncertainty of mutagenic results (Aggarwal et al., 2024; Ali et al., 2022; Imran & Ghosh, 2024; Manzanares et al., 2016; Molitorisová et al., 2024; Mushtaq et al., 2018; Smith et al., 2023). Although these methods create genetic variation, the resulting mutations are unpredictable and may not consistently reflect the desired characteristics for enhancing crops. The inherent unpredictability of this situation presents difficulties in effectively choosing and implementing mutants with specific agricultural advantages. Stress-induced mutagenesis involves subjecting crops to environmental stressors to provoke genetic variation. Nevertheless, the absence of accuracy in regulating mutations' particular nature and magnitude presents difficulties. Diverse stress conditions elicit distinct responses, and the consequent mutagenic effects may not consistently confer advantages or pertain to the

desired traits. Obtaining a more precise and regulated stress-induced mutagenesis poses a difficulty in crop breeding. Although ionising radiation has been employed as a mutagenic factor in crop breeding, our comprehension of the molecular mechanisms underlying plant radiation responses is still advancing. A comprehensive understanding of the mechanisms that drive radiation-induced effects, including DNA damage and repair, stress signalling pathways and radiation-responsive genes, is crucial. A more thorough comprehension of these molecular processes will improve techniques for utilising radiation-induced mutagenesis. The ongoing challenge lies in incorporating genomic data into understanding radiation-induced and stress-induced mutagenesis. Although next-generation sequencing technologies yield extensive genetic data, effectively using this information for crop enhancement requires advanced bioinformatics tools and analyses. It is essential to create efficient frameworks for incorporating genomics data into breeding programmes to maximise the effectiveness of mutagenic strategies. Using radiation-induced effects and stress-induced mutagenesis in crop breeding gives rise to apprehensions regarding unintended repercussions. The introduction of mutations, whether caused by ionising radiation or exposure to stress, can result in unexpected alterations in the plant genome, which may impact traits beyond the intended enhancements. A crucial ethical consideration is to prevent these unintended consequences from posing risks to human health, the environment or the stability of agricultural ecosystems. Releasing genetically modified crops into the atmosphere prompts concerns regarding the possible ecological consequences. It is crucial to comprehend how these genetic variations engage with the surrounding ecosystems, encompassing organisms that are not the intended targets, the microorganisms in the soil and the adjacent crops. Environmental impact assessments are necessary to evaluate the potential ecological consequences of deploying crops generated through radiation-induced effects or stress-induced mutagenesis. Prolonged exposure to stressors or mutagenic agents can have enduring impacts on soil health. It is essential to comprehend the effects on soil microbiota, nutrient cycling and the overall resilience of the ecosystem. To ensure sustainable agricultural practices, it is necessary to evaluate the long-term impacts of mutagenesis on soil health and adopt measures to minimise any potential adverse effects. The continuous challenge lies in developing strong regulatory frameworks to govern the release of genetically modified crops. A thorough assessment is necessary to evaluate the potential hazards linked to genetic alterations caused by radiation or stress. Establishing transparent and scientifically rigorous regulatory procedures is crucial to guarantee the safe implementation of genetically modified crops in agriculture. We must carefully navigate the ethical dilemma of balancing the imperative for innovation with rigorous safety evaluation. The progress made in genome editing technologies, such as CRISPR-Cas9, shows potential for achieving more accurate and regulated mutagenesis. One can overcome the uncertainty inherent in conventional mutagenesis techniques by employing these methods to induce particular mutations linked to stress tolerance or desirable agricultural characteristics. Advancing precision mutagenesis techniques can significantly improve the effectiveness and precision of crop breeding. By combining various omics techniques such as genomics, transcriptomics, proteomics and

metabolomics, a comprehensive comprehension of the molecular reactions to radiation and stress-induced mutagenesis can be achieved. This comprehensive methodology can decipher intricate regulatory networks, pinpoint crucial molecular participants and facilitate the choice of mutants with desired characteristics. Integrated omics analyses are a promising avenue for research that can greatly improve our comprehension of mutagenic processes. Synthetic biology provides novel techniques for the design and manipulation of biological systems. Utilising synthetic biology principles in crop breeding entails creating customised stress-responsive pathways, selectively introducing advantageous genes and accurately manipulating genetic components. Utilising artificial biology applications in radiation-induced effects and stress-induced mutagenesis can result in significant advancements in the development of crops with customised reactions to particular stressors. Advanced systems biology modelling techniques can enhance our comprehension of the intricate interactions occurring within plant systems undergoing mutagenesis. By incorporating genetic, physiological and environmental factors, computational models can simulate the results of mutagenesis in different situations. Systems biology modelling can guide experimental design, anticipate mutagenic results and optimise approaches to enhance crop resilience. Developing sustainable mutagenesis practices entails refining techniques to minimise unintended repercussions and environmental effects. By integrating the principles of agroecology and sustainable agriculture into mutagenesis strategies, we can guarantee that crop breeding practices align with the larger objectives of environmental stewardship, resource conservation and biodiversity preservation. These innovative approaches' challenges and future directions highlight the complexity of harnessing radiation-induced effects and stress-induced mutagenesis. To achieve responsible and sustainable crop improvement, it is crucial to address the existing limitations in our understanding, carefully navigate ethical considerations and ensure safety when deploying mutant crops. Future research areas such as precision mutagenesis techniques, integrated omics approaches, synthetic biology applications and systems biology modelling hold the potential to fully exploit mutagenic strategies for improving crop resilience. As scientists further investigate these possibilities, it is crucial to adopt a fair and cooperative strategy to maximise the advantages of mutagenesis while minimising any potential hazards for the future of agriculture.

7.12 Conclusion

To summarise, investigating the impacts of radiation and stress on crops as methods to improve their ability to withstand challenges represents a novel area of study in agricultural science. The dynamic interaction between these two methods presents a hopeful opportunity for developing crop varieties that can endure global agriculture's constantly evolving and demanding conditions. Exploring the intricate mechanisms, applications, challenges and future directions of utilising these mutagenic strategies uncovers these innovations' potential advantages and complexities. The

importance of radiation-induced effects lies in its capacity to generate genetic variability using deliberate exposure to ionising radiation. This variability offers an opportunity to choose characteristics that improve the ability of crops to withstand stress, resist diseases and adapt to different environments. Investigating induced radioresistance introduces a new aspect: plants are prepared to endure future stressors, enhancing crop resilience. Identifying genes that respond to radiation and incorporating this information into breeding programmes offer a more focused and precise method for developing crop varieties that are resilient to stress. Conversely, stress-induced mutagenesis, caused by exposure to different environmental stressors, speeds up breeding by introducing genetic diversity within a single generation. Employing this regulated method makes it possible to investigate new attributes, improve stress resistance and potentially uncover agriculturally advantageous traits. Using stress-induced mutagenesis alongside advanced breeding methods such as marker-assisted selection and genomics can enhance the accuracy and effectiveness of crop development for desired characteristics. Nevertheless, despite the promises of improved crop resilience, specific challenges require careful attention. The inherent uncertainty of mutagenic results presents a substantial obstacle in attaining specific enhancements, thus requiring progress in precision mutagenesis methods. The significance of responsible implementation and regulatory frameworks is emphasised by ethical considerations and safety concerns to guarantee the safety of the environment and consumers. Tackling these challenges will be crucial for accepting and implementing these mutagenic strategies in mainstream agriculture. Exploring future research directions is vital for fully harnessing the potential of radiation-induced effects and stress-induced mutagenesis. Methods for precise genetic modification, comprehensive analysis of biological systems, practical uses of synthetic biology and environmentally friendly genetic modification practices are all ways to address current constraints and optimise the advantages of these cutting-edge strategies. Systems biology modelling is increasingly recognised as a potent tool for simulating and predicting outcomes. It helps guide experimental design and optimise strategies for enhancing crop improvement. Investigating the consequences of radiation exposure and stress-induced genetic changes represents a significant change in crop breeding methods, emphasising more adaptable, practical and focused approaches. To ensure the survival of crops in the face of climate change, emerging diseases and limited resources, it is necessary to incorporate these mutagenic strategies into conventional agricultural practices. In the face of growing threats to global food security, the collective endeavours of scientists, policymakers and stakeholders will play a vital role in fully harnessing the benefits of radiation-induced effects and stress-induced mutagenesis. This will contribute to the resilience of crops and guarantee a sustainable and productive future for agriculture.

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Chapter 8

High-Throughput Sequencing for Climate Resilient Agriculture: Integrative Genomic Strategies and Modern Breeding Technologies



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8.1 Background

Climate change poses significant challenges to global food security and agricultural stability. Rising temperatures affect plant biology, photosynthesis, and crop growing seasons (Aslam, 2023), while irregular precipitation patterns lead to droughts and floods, impacting water availability and causing soil erosion (Vermeulen et al., 2012). Extreme weather events like hurricanes and droughts can devastate crops and increase pest and disease spread. Such challenges threaten agricultural systems worldwide, especially in developing countries heavily reliant on agriculture. To address these issues, adopting climate-resilient agricultural practices is crucial. Climate smart agriculture (CSA) practices mitigate climate impacts on crop production at farm and regional levels (Kien et al., 2023). Initiatives like India's National

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Innovations in Climate Resilient Agriculture (NICRA) aim to promote these practices despite obstacles like cost and infrastructure limitations.

Immediate action is essential. Implementing CSA techniques, enhancing awareness, and investing in infrastructure are critical steps. Developing weather-resistant crop varieties through genetic engineering and employing advanced agricultural techniques such as precision farming and water conservation are vital (Bailey-Serres et al., 2019). Crop diversification also buffers against climate impacts. Policies supporting sustainable practices and technological innovation are essential for resilient agriculture (Bailey-Serres et al., 2019). Incorporating information technology like big data and predictive analytics can optimize farming decisions amid climatic uncertainty, fostering a sustainable and secure global food system. Transitioning to climate-resilient agriculture, blending scientific advancements with traditional knowledge, is crucial for safeguarding agricultural landscapes and communities worldwide.

8.2 Understanding Climate-Resilient Agriculture

8.2.1 *Climate Resilience in Agriculture*

Climate resilience in agriculture is crucial for adapting to and recovering from climate change challenges, ensuring the continued functionality of agricultural systems despite increasing temperatures, erratic rainfall, and extreme weather. Key to this resilience is the development and adoption of climate-resilient crops, which thrive under changing conditions (Saab, 2016). Utilizing lesser-known wild crops and prioritizing crop wild relatives also bolster global food and nutritional security (Singh et al., 2019; Satori et al., 2022).

Climate-smart agricultural practices enhance agro-ecosystems' capacity to withstand, respond to, and recover from climate disturbances. Technologies and interventions, such as climate-resilient agro-technologies and climate-smart practices for small-holder farming, support farmers in adapting to climate impacts. Transformative research strategies and innovative approaches are essential for developing climate-resilient agricultural systems. Public policies also play a crucial role in supporting the development of resilient agroecosystems, highlighting the importance of policy interventions in building climate resilience in agriculture (Mikery-Gutiérrez et al., 2020).

Adaptability in agriculture is crucial for mitigating climate change impacts through strategies like using genetically adapted crops, adjusting planting and harvesting times, and employing precision agriculture. Climate change exacerbates issues in vulnerable regions, requiring continuous adaptation to changing conditions (Adhikari, 2018). Mediterranean regions, facing increased drought and high temperatures, need specific adaptation strategies (Pozo et al., 2019).

Adaptability for multifunctionality in agricultural systems involves balancing socio-ecological aspects, necessitating transformative changes. Slight climate changes significantly impact agriculture due to its dependence on the natural

environment. Decision-making for adaptation must balance different system aspects and functions. Extreme weather events increase pest and weed issues, prompting changes in farming practices. Designing adaptation options for dryland agriculture is crucial (Ahmed et al., 2022). Shifts in agricultural practices build on traditionally adapted agronomic methods. Different systems have unique adaptation needs, highlighting the importance of justice in agricultural adaptation.

Recovery capabilities in agriculture are essential for restoring productivity after climatic shocks. Key practices include enhancing soil health, water retention, preventing erosion, and employing crop rotations. Resilient seed banks and planting materials are vital for rejuvenating agriculture post-extreme weather events, allowing agricultural systems to adapt over time (Kliem, 2024). Soil seed banks are crucial for ecosystem recovery post-disturbance, initiating restoration even after heavy invasions of non-native species (Dalton et al., 2017). The regenerative potential of soil seed banks is critical for restoring ecological functions on abandoned agricultural lands. Long-term restoration efforts can enhance vegetation resilience by altering the soil seed bank (Guo et al., 2023). The seed bank of specific plant species, like *Halophila ovalis*, aids resilience through re-establishment. The composition of dormant propagules in soil seed banks directly influences aboveground vegetation dynamics. Assessing changes in seed bank species composition is crucial for estimating the restoration potential of native communities.

However, increased grazing intensity can exhaust seed banks if species losses exceed a threshold. In conclusion, building climate resilience in agriculture through soil health enhancement, water retention, and resilient seed banks is crucial for food security, supporting livelihoods, and maintaining ecosystem services in an unpredictable climate. Understanding soil seed bank dynamics is essential for effective ecosystem restoration.

8.2.2 Challenges of Climate Change for Traditional Farming

Climate change alters traditional agricultural practices by shifting seasonal patterns, affecting planting and harvesting times (Tao et al., 2008). Warmer temperatures extend growing seasons in northern latitudes but reduce viable planting days in tropical areas, causing water stress and lower yields (Tao et al., 2008). Farmers struggle to adapt schedules, often resulting in reduced output (Tao et al., 2008). Understanding local crop responses to climate variability is crucial for predicting future agricultural impacts (Tao et al., 2008). Decision-making regarding crop selection and use of inputs like fertilizers and pesticides influences adaptation to these changes (Prasanna et al., 2022).

The length of the growing season affects planting and harvesting schedules. Remote sensing technologies help monitor agricultural activities and optimize decisions, such as irrigation management. These technologies also aid in tracking crop phenology and improving field management. Adapting to climate shifts requires understanding regional impacts and developing strategies using climate models and projections. Advanced technologies like deep learning on satellite imagery can map

seasonal agricultural land use, assisting in planning and forecasting production (Debella-Gilo & Gjertsen, 2021).

Climate change alters the landscape of agricultural pests and diseases by changing temperature and humidity, expanding pests' geographical range (Finckh et al., 2000). Warmer temperatures allow pests like the coffee berry borer to move into higher altitudes, affecting previously safe crops (Finckh et al., 2000). Increased humidity and temperature also lead to more fungal diseases, requiring new, often unavailable pest management strategies (Finckh et al., 2000). Climate change creates new niches for pests, enabling them to spread to new regions and destabilizing global food production (Crossley et al., 2024).

Regions like the tropical Andes face higher risks of crop yield losses and food insecurity due to altered suitability for crops and cultivation systems (Tito et al., 2018). Adaptive management strategies are necessary to cope with changing pest dynamics (Sutherst et al., 2011). Climate change impacts crop pest and disease distribution, affecting food crops in regions like Zambia (Nguru & Mwongera, 2023). Shifting suitable conditions for pest outbreaks alter threats and required management regimes for farmers (Chaloner et al., 2021).

Climate change threatens established agricultural practices by introducing unpredictability and disrupting traditional knowledge. Increased extreme weather events, like droughts and floods, lead to immediate losses and long-term land degradation, impacting productivity and ecological balance (Cogato et al., 2019; Arreyndip, 2021). Developing countries face rising challenges, with climate change affecting crop growth and production (Marmai et al., 2022). Regions like the North China Plain and Central Vietnam have seen significant impacts on crop yields and food security (Song et al., 2022; Quang et al., 2021). Adaptation strategies include improved crop management, complex rice systems for yield stability, agricultural insurance schemes, and diversification to build economic resilience (Rahman et al., 2024; Khumairoh et al., 2018; Guo et al., 2022; Chonabayashi et al., 2020).

New pests, diseases, and changing growing seasons threaten global food security, especially in resource-limited developing countries. Adaptive strategies, including developing climate-resilient crops, adopting advanced agricultural technologies, and revising farming practices, are crucial (Khan et al., 2021). Technological innovations, such as hyperspectral imaging and remote sensing, provide solutions and early warnings to enhance food security (Khanal et al., 2020). Digital agriculture security measures are essential to protect against threats (Friha et al., 2022). Smart practices using IoT and AI can help balance food supply and demand, and big data analytics is expected to boost agricultural productivity (Alreshidi, 2019; Lassoued et al., 2021).

8.2.3 The Role of Innovative Technologies

Climate change poses significant challenges to agriculture, requiring innovative solutions to boost crop resilience and sustainability. Advanced technologies like high-throughput sequencing (HTS) enable precise genetic modifications to enhance

crop tolerance to climate stressors and develop herbicide-tolerant crops (Yuan et al., 2023; Chaturvedi et al., 2017; Lamichhane et al., 2017). HTS also supports the resilience of crops by integrating wild relatives and assessing production systems' resilience (Satori et al., 2022; Zampieri et al., 2020). Additionally, leveraging soil microorganisms can further improve crop resilience (Paolinelli et al., 2023). Embracing these technologies is essential for maintaining global food security amid climate change.

8.2.3.1 Genetic Improvement of Crops

High-throughput sequencing (HTS) technology has revolutionized crop genetic improvement by enabling rapid, precise genetic analysis. HTS helps identify genetic variants for traits like drought tolerance and pest resistance, crucial for adapting crops to climate change. For instance, HTS has been used to develop flood-resistant rice varieties in Asia. Integrating HTS with precision phenomics and genomics enhances the development of drought and heat-tolerant crops, boosting resilience and yield under stress (Prasad et al., 2021). This multidisciplinary approach is vital for sustaining global productivity, particularly under heat stress (Jha et al., 2017). HTS's success across fields like human genetics and cancer research underscores its transformative potential in crop breeding and agricultural practices (Duitama et al., 2014).

8.2.3.2 Precision Agriculture

Precision agriculture uses data and technology, such as GPS mapping, soil scanning, drones, and IoT sensors, to improve farming accuracy. It enhances resource application, reduces costs, lowers environmental impact, and increases crop yields by addressing plant needs more precisely. Big data analytics, machine learning, and AI facilitate real-time monitoring, predictive analysis, and disease detection (Morota et al., 2018; Salam & Shah, 2019). Despite its benefits, challenges like data privacy, technology costs, and the need for farmer training hinder adoption. Addressing these issues with better privacy measures, training, and communication is essential for widespread implementation (Sanders et al., 2022).

8.2.3.3 Synthetic Biology and CRISPR

Synthetic biology, combined with CRISPR-Cas9 genome editing, is transforming agriculture by enabling precise DNA modifications in crops. This technology allows for the introduction of beneficial traits, such as drought resistance, into plants like maize, mitigating the effects of climate change (Goold et al., 2018; Tian et al., 2021). Synthetic biology also facilitates the creation of novel gene networks and biosensors, enhancing crop traits and sustainability (Yan et al., 2018). By integrating engineering principles with plant biology, synthetic biology improves crop

nutrition, pest resistance, and environmental resilience (Schroeder & Saha, 2019; Fantinel et al., 2022). Beyond crop improvement, it contributes to sustainable bio-energy production and bio-based materials, offering greener alternatives to traditional manufacturing (Ramírez Rojas et al., 2022). As synthetic biology advances, it presents both challenges and opportunities for innovation in agriculture and related sectors (Chugh et al., 2015).

8.2.3.4 Integration with Global Information Systems

Advanced technologies and global information systems are crucial for agriculture, offering predictive insights for strategic planning. They enable weather, pest, and crop yield predictions, aiding in informed decision-making. Geospatial technology and remote sensing improve monitoring of soil and crop conditions, promoting sustainable practices and food security (Pandey & Pandey, 2023). Digital soil maps and high-throughput sequencing (HTS) support resilient crop development and optimized inputs (Qin, 2022). Integrating these technologies enhances yield stability and agricultural resilience under climate change, contributing to global food security (Zougmore et al., 2014; Pandey & Pandey, 2023).

8.3 Basics of High-Throughput Sequencing

High-throughput sequencing (HTS), or next-generation sequencing (NGS), has revolutionized genomics by enabling rapid and comprehensive DNA and RNA sequencing. Unlike traditional methods like Sanger sequencing, HTS provides detailed genomic and transcriptomic data quickly and affordably.

HTS technologies include: It is a transformative technology that has enabled breakthroughs in genomics, offering high throughput, scalability, and cost-effectiveness. This chapter will explore HTS's role in improving agricultural practices to adapt to climate change, focusing on its use in crop identification, breeding, and cultivation.

8.3.1 High-Throughput Sequencing Technologies

High-throughput sequencing (HTS), or next-generation sequencing (NGS), has revolutionized genomics by rapidly sequencing vast amounts of DNA and RNA. Key HTS technologies include Illumina sequencing, used in whole-genome and transcriptome projects, and long-read platforms like PacBio and Oxford Nanopore, which aid in assembling complex genomes. HTS has advanced plant and microbial genomics, enhancing genetic diversity understanding and crop improvement (Diao et al., 2014; Wick et al., 2017) (Table 8.1).

Table 8.1 Techniques used to find out the QTLs, linked markers responsible to biotic and abiotic stresses

S. no	Techniques used	Remarks	Study
1	GWAS, root phenotyping methods	Identified genes, transcription factors, and QTLs involved in root growth and development during drought	Kalra et al. (2024)
2	MAGIC population, GWAS	Identified markers and candidate genes like CaTIFY4b and FRIGIDA linked to drought tolerance	Thudi et al. (2024)
3	GWAS, Diallel analysis	Identified molecular markers associated with disease resistance and post-harvest traits in coffee	Ferrão et al. (2024)
4	GWAS	Identified QTLs linked to drought-related traits and nitrogen use efficiency in wheat	Koua et al. (2024)
5	lncRNA transcriptome analysis	Identified novel lncRNAs and mRNAs interacting in response to drought stress	Ackah et al. (2024)
6	Proteomics (iTRAQ)	Identified key proteins conferring drought tolerance in wheat	Nouraei et al. (2022)
7	GWAS, transcriptome analysis	Identified potential genes controlling anaerobic germination tolerance in rice	Thapa et al. (2024)
8	Phenotyping, molecular mechanisms	Identified novel sources for heat stress tolerance in maize	Djalovic et al. (2024)
9	Genomic, transcriptomic, proteomic, metabolomic analysis	Advanced knowledge on cold tolerance mechanisms in staple crops	Jan et al. (2024)
10	Genomic tools, marker development	Outlined strategies for controlling plasticity traits in constrained soil conditions in wheat	Bhoite et al. (2024)
11	Genome-wide identification, phylogenetic analysis	Revealed conservation of salt tolerance mechanisms in Rosaceae species	Acharya et al. (2024)
12	GWAS	Identified novel QTLs for pre-harvest sprouting resistance in wheat	Dallinger et al. (2024)
13	Genome-wide analysis, gene duplication analysis	Revealed potential roles of ZoMYBs in anti-stress responses in ginger	Yao et al. (2024)
14	Chromosome segment substitution lines	Characterized genetic variation from progenitor species for stress tolerance in wheat	Horsnell et al. (2024)
15	RADseq, population genomic analysis	Identified sites under diversifying selection linked to stress response in <i>Reaumuria trigyna</i>	Dang et al. (2024)
16	Pangenome, de novo genome assemblies	Identified noncore genes enriched in stress and defense response in cowpea	Liang et al. (2024)
17	Machine learning algorithms	Developed a model to predict stress-responsive genes in plants	Meher et al. (2022)

8.3.1.1 Ion Torrent Sequencing

Detects pH changes during nucleotide incorporation for fast sequencing, ideal for targeted applications.

8.3.1.2 Nanopore Sequencing

Measures changes in electrical current as DNA passes through a nanopore, providing long reads and direct RNA sequencing.

8.3.1.3 Single-Molecule Real-Time (SMRT) Sequencing

Monitors DNA polymerase activity in real time for long, accurate reads, useful for complex genomic regions and epigenetic studies. HTS has significantly advanced disease research, identifying genetic variations associated with disorders, and enhanced understanding of complex traits through genome-wide association studies (GWAS). In metagenomics, HTS has revealed microbial diversity and functional capabilities, while in epigenomics, it has mapped DNA and histone modifications to elucidate gene regulation.

8.3.1.4 Illumina Sequencing (Short-Read)

Illumina sequencing is a highly accurate and efficient high-throughput technology using sequencing by synthesis (SBS) to simultaneously sequence millions of DNA fragments. It produces read lengths of 50–300 bases, making it ideal for SNP detection, RNA sequencing, and metagenomics. In agriculture, it aids in genomic studies, disease identification, and trait selection for breeding. It has applications in analyzing crop transcriptomes, identifying bacterial species, and pathogen detection in livestock. Illumina sequencing is also crucial in public health for infectious disease surveillance due to its precision and versatility (Duarte et al., [2020](#)).

8.3.1.5 PacBio Sequencing (Long-Read)

PacBio sequencing provides long-read technology, typically ranging from 10 to 60 kb, ideal for resolving complex genomic regions like repetitive sequences and structural variants. It excels in de novo genome assembly, epigenetic profiling, and transcriptome studies. In agriculture, it enhances genome annotation and breeding strategies for traits such as disease resistance and yield optimization. The PacBio RS platform offers high-quality, gap-free genome sequences and has been used for chromosome-scale assemblies in various species. Compared to other technologies like Oxford Nanopore, PacBio's long reads offer significant advantages in sequencing throughput and accuracy (Zhang et al., [2023](#)).

8.3.1.6 Oxford Nanopore Technologies (ONT)

Oxford Nanopore Technologies (ONT) provides long-read sequencing by detecting changes in electrical conductivity as nucleic acids pass through a nanopore, enabling direct and real-time sequencing without fluorescent labeling. ONT's technology supports the sequencing of entire chromosomes in single reads, crucial for applications like pathogen identification, environmental monitoring, and genome mapping in agriculture. Its cost-effectiveness and ability to multiplex samples make it particularly useful for bacterial genomics. ONT excels in analyzing structural variations and fine-mapping plant genomes, and when combined with other technologies like PacBio, it facilitates chromosome-level genome assemblies. ONT's long-read capabilities enhance our understanding of genetic variations and transcript isoforms in various species (Wick et al., 2021).

8.3.2 Role in Agricultural Genomics

The integration of high-throughput sequencing (HTS) in agricultural genomics has revolutionized breeding by enabling detailed exploration of genomic diversity and accelerating the development of new crop varieties through marker-assisted and genomic selection (Olalde et al., 2014). HTS technologies are essential for capturing genetic complexity and are expected to further advance sustainable agriculture by expediting breeding programs (Olalde et al., 2014). Genomic resources have been crucial in understanding traits in important species and enhancing crop breeding for food security and environmental sustainability (Zhang et al., 2022).

8.3.3 The Sequencing Process and Data Generation

High-throughput sequencing (HTS) has revolutionized genomics by enabling rapid, cost-effective generation of vast data, crucial for various applications in agriculture, biomedicine, and environmental studies (Tang et al., 2020). HTS involves sample preparation, sequencing, and data analysis, ensuring high-quality data. It has advanced research in areas such as crop phenotyping, microbial diversity, cancer studies, and immunogenomics (Jia et al., 2022). HTS's versatility and efficiency make it a cornerstone of modern genomics research across multiple disciplines.

8.3.3.1 Sample Preparation

Sample preparation is vital in high-throughput sequencing (HTS), involving the extraction and fragmentation of DNA/RNA, followed by library preparation with specialized adapters. Quality and purity are crucial for successful sequencing.

Automation has improved reproducibility and throughput in complex protocols, while novel methods and kits streamline workflows and reduce input requirements. Advances like bead-linked transposomes and fluorescent amplification have further simplified library preparation, enhancing efficiency in next-generation sequencing (Chiniquy et al., 2020).

8.3.3.2 Sequencing

Illumina and Oxford Nanopore offer distinct DNA sequencing methods: Illumina uses clonal amplification with reversible terminations for base determination, while Oxford Nanopore sequences DNA in real-time by detecting changes in electrical conductivity as DNA passes through a nanopore. These technologies have revolutionized genomics, enabling detailed analyses of genomes, transcriptomes, and microbial communities. The choice of platform is crucial, as it can significantly impact research outcomes (Rieber et al., 2013).

8.3.3.3 Data Analysis

Genome sequencing technologies have rapidly advanced, generating vast raw data that require processing with bioinformatics tools. Quality control is the first step, removing low-quality reads before aligning to a reference genome or assembling *de novo* (Zhang et al., 2012). Challenges with short-read technologies, such as repetitive content and sequencing errors, complicate assemblies. Long-read technologies, despite higher error rates, enable complete genome assemblies. New tools like Tigmint and Tricycler improve assembly accuracy, particularly for complex genomes (Wick et al., 2021).

8.3.3.4 Types of Data Generated and Their Implications for Agriculture

Advanced sequencing technologies like whole-genome sequencing (WGS), RNA sequencing (RNA-Seq), metagenomics, and epigenomics have profound implications for agriculture. WGS identifies genetic variations for marker-assisted breeding, while RNA-Seq reveals gene expression patterns, aiding in genetic engineering. Metagenomics analyzes soil microbial communities to develop biofertilizers and biopesticides, enhancing crop productivity. Epigenomics studies environmental influences on gene expression, guiding the development of crops adapted to adverse conditions. Integrating these technologies improves crop performance, yield stability, and global food security. Metagenomic studies highlight the crucial role of microbial communities in nutrient cycling and plant health, revealing the impacts of environmental factors and agricultural practices (Iquebal et al., 2022). This knowledge can revolutionize agricultural practices, addressing food security challenges through enhanced crop productivity and sustainability.

8.3.4 HTS Versus Traditional Methods

High-throughput sequencing (HTS) has revolutionized genomics by offering significant advantages over traditional Sanger sequencing, including higher throughput, faster processing, cost efficiency, and the ability to handle complex genetic data (Langridge et al., 2009). HTS can sequence millions of DNA fragments simultaneously, enabling large-scale projects like whole-genome sequencing and metagenomics, which are beyond the reach of Sanger sequencing. It also produces entire genome data in a single day, crucial for time-sensitive research, and is more cost-effective, making large-scale studies feasible (Langridge et al., 2009). HTS has been pivotal in fields such as agriculture, aiding in the development of crops with desired traits, and in cancer genomics, allowing comprehensive analysis of complex structural variations. Additionally, HTS has enabled population-level genetic studies, such as those on *Neisseria* species. Overall, HTS has expanded the possibilities for research, providing deeper insights into genetic material and facilitating ground-breaking discoveries across various fields.

8.4 Applications of High-Throughput Sequencing in Agriculture

8.4.1 Enhancing Crop Genetic Profiles

High-throughput sequencing (HTS) technologies have revolutionized agricultural genomics by enabling rapid and precise identification of key agronomic traits, particularly those related to climate resilience, such as drought tolerance and pest resistance. HTS has facilitated comprehensive chromatin mapping, accelerated the development of stress-tolerant crops, and enhanced the availability of complete chloroplast genomes for comparative studies. The technology's depth of coverage and ability to sequence mitochondrial genomes have significantly improved genomic resolution and plant molecular breeding. HTS has also advanced functional genomics, enabling rapid discovery of new alleles and characterization of complex genomic regions using CRISPR-Cas9 (Fiol et al., 2022). Overall, HTS has greatly enhanced crop improvement efforts, contributing to sustainable agriculture and food security.

8.4.1.1 Climate-Resilient Traits: Molecular Breeding Strategies

Molecular breeding strategies leveraging high-throughput sequencing (HTS) data have significantly advanced agriculture by identifying genetic markers linked to traits like drought tolerance and pest resistance. Genome-wide association studies (GWAS) and genomic selection (GS) have been particularly successful in plants, enabling the

identification and utilization of functional molecular markers for improved crop traits (Wang et al., 2021). Techniques like marker-assisted breeding and genome-wide selection are critical for developing drought-tolerant cultivars, enhancing food security amid changing climates. Recent advances, including transgenic approaches and genome editing, offer more precise and efficient methods for crop improvement (Liu & Qin, 2021). Overall, integrating these strategies into breeding programs is crucial for developing resilient crops and ensuring agricultural sustainability.

8.4.1.1.1 Drought Tolerance

Drought tolerance is critical for plants amid climate variability, and high-throughput sequencing (HTS) is instrumental in identifying genes and regulatory sequences involved in drought response. Key studies have highlighted genes linked to drought tolerance through root system architecture. For instance, found that a homeodomain-START transcription factor enhances root development in Arabidopsis. Kulkarni et al. (2017) identified genes like DRO1 and ERECTA that improve drought tolerance by regulating root traits and transpiration. Li et al. (2023) emphasized the role of genes such as ZmCIPK3 in maize and quantitative traits in soybeans. Transcription factors like OsNAC6 (Lee et al., 2017) and NAC-domain factors (Chung et al., 2018) have been linked to drought tolerance mechanisms. Additionally, CKX gene manipulation and candidate gene validation for metaxylem development in rice are promising for enhancing drought tolerance (Sharma et al., 2022).

8.4.1.1.2 Pest Resistance

Pest resistance is vital for agricultural productivity, and high-throughput sequencing (HTS) aids in identifying genetic variations that enhance plant defences. For example, the GhLac1 gene in cotton improves pest and pathogen resistance (Hu et al., 2017). Researchers have identified key resistance genes and processes through molecular genetics, revealing genetic diversity's role in pest resistance, such as Norway spruce's resistance to white pine weevils (Broekgaarden et al., 2011; Zas et al., 2017). Tolerance mechanisms also play a role in pest resistance, influencing insect herbivores. Genetic diversity in wild genotypes offers potential for developing resistant varieties. Combining genetic resistance with Bt maize is explored for pests like the fall armyworm (Prasanna et al., 2022), while insect adaptation through detoxification gene variations increases resistance. Integrating genetic resources and modifications aims to create pest-resistant crops.

8.4.1.1.3 Nutrient Efficiency

Nutrient efficiency is essential for sustainable agriculture, especially in low-input systems. High-throughput sequencing (HTS) identifies genes enhancing nutrient uptake and utilization, which can be integrated into breeding programs via

marker-assisted selection (MAS) or CRISPR-Cas9. Key factors for nutrient uptake include root morphology and ion accumulation. Genetic variation influences nutrient efficiency, and signaling pathways like the Ca^{2+} pathway play a role in nutrient uptake (Li et al., 2006). Enhancing nutrient efficiency involves genetic manipulation to improve traits such as root proliferation and salt tolerance. Mycorrhizal fungi and microorganisms also impact nutrient uptake, with varying effects based on plant genotype and nutrient availability.

8.4.1.2 Development of Stress-Tolerant Varieties

Developing stress-tolerant crop varieties is key for food security amid climate change. High-throughput sequencing (HTS) accelerates this by identifying genetic traits and speeding up breeding cycles through genomic selection (Ahmar et al., 2020). Techniques like high-throughput phenotyping (HTP) and speed breeding further expedite plant breeding (Ahmar et al., 2020). Advances in doubled haploid (DH) and single seed descent (SSD) techniques enable the production of numerous inbred lines annually, aiding trait selection (dos Santos et al., 2022). Genomic selection has improved selection accuracy and genetic gain, particularly in intercrop breeding and using low-coverage nanopore sequencing. Next-generation sequencing has enhanced population genomics data, aiding crop domestication and breeding insights. Speed breeding advances the breeding process by manipulating environmental conditions. While genomic prediction boosts selection efficiency, cost constraints may limit adoption, and data sharing is essential for rapid crop variety development. Incorporating genetic loci into marker-assisted selection can accelerate genetic gains crucial for food security (Sharma et al., 2021).

8.4.1.2.1 Accelerated Breeding Cycles

High-throughput sequencing (HTS) technologies have accelerated breeding cycles by enabling rapid genetic data analysis and selection based on genetic profiles rather than field traits (Yang et al., 2020). Speed breeding, generating 4–6 generations per year, complements HTS by further shortening breeding durations. Integrating HTS, speed breeding, and precision phenotyping enhances genetic gains in crops like pearl millet (Yadav et al., 2021) and maize, particularly for traits such as drought tolerance. Emerging genomic tools also boost legume breeding to address global population demands. Breeder chips and molecular-assisted selection in wheat emphasize the need for accelerated resistance breeding. Comprehensive speed breeding systems, along with genome-wide association studies and genomic selection, are effective for improving traits like drought tolerance in rice (Kumar et al., 2023). Genotyping-by-sequencing (GBS) and cost-effective next-generation sequencing (NGS) technologies facilitate routine screening in crop breeding. Overall, integrating advanced genomic and phenomic tools with speed breeding strategies significantly advances genetic improvement in crops (Kumar et al., 2021).

8.4.1.2.2 Enhanced Testing Efficiency

Enhanced testing efficiency in plant breeding relies on high-throughput sequencing (HTS) for detailed genetic characterization and virus diagnostics, expanding the understanding of plant-pathogen interactions. Field-based phenomics and high-throughput plant phenotyping (HTPP) enable accurate evaluation of traits under stress conditions. Next-generation sequencing (NGS) provides essential markers and genetic maps, while machine learning (ML) algorithms and genomic selection improve breeding efficiency and genotype commercialization. Overall, these technologies revolutionize plant breeding by enhancing the genotype-phenotype analysis of complex traits (Perez-de-Castro et al., 2012).

8.4.1.2.3 Integration of Multi-Trait Selection

The integration of multi-trait selection using high-throughput sequencing (HTS) represents a major advancement in plant breeding. HTS enables the simultaneous monitoring of multiple traits, aiding in the development of crop varieties that are stress-tolerant, high-yielding, and of good quality (Genievskaya et al., 2018). It facilitates genome-wide association studies (GWAS) to identify key marker-trait associations, improving traits like heading time and grain weight (Genievskaya et al., 2018). This approach enhances crop resilience to environmental stresses and supports global food security amidst climate change (Genievskaya et al., 2018; Prasad et al., 2021). Additionally, post-genomic tools and precision phenotyping improve the assessment of traits, accelerating the development of climate-resilient varieties. This holistic strategy is crucial for advancing breeding efforts and ensuring food security.

8.4.2 *Precision Agriculture and Data-Driven Decisions*

High-throughput sequencing (HTS) is essential in precision agriculture for data-driven decision-making. HTS enables high-resolution crop monitoring through satellite and airborne platforms, optimizing resources like water, fertilizers, and pesticides. It provides accurate, non-destructive monitoring of biomass and aids in identifying novel viruses affecting crops like maize (Wang et al., 2021). HTS integrated with UAVs and remote sensing enhances monitoring of crop conditions and growth phases, as seen in rice management. Additionally, combining HTS with machine learning and geospatial analysis improves crop and soil health assessments and yield predictions.

8.4.2.1 Monitoring Crop Health

High-throughput sequencing (HTS) is crucial for monitoring crop health by providing real-time insights into plant stress responses (Hasanuzzaman et al., 2013). HTS enables rapid pathogen detection, detailed transcriptomic analysis, and large-scale

phenotyping, aiding in early disease detection and effective crop management (Hasanuzzaman et al., 2013). It helps identify genetic responses to stressors like drought, pests, and high temperatures, impacting traits such as male sterility and metabolic profiles (Li, 2023; Khan et al., 2022). HTS also explores plant resilience to salinity stress, including interactions with halotolerant bacteria and responses in mungbean.

8.4.2.2 Optimizing Resource Use

High-throughput sequencing (HTS) is transforming agriculture by optimizing resource use and enhancing sustainability. HTS provides detailed genetic insights, enabling precise resource management, such as targeted water and fertilizer application, which conserves resources and reduces environmental impact (Ye et al., 2021). It also supports efficient pesticide use by identifying disease-resistant variants and specific pathogens, minimizing chemical use and environmental damage. Overall, HTS enhances productivity and aligns with sustainability goals, crucial for food security (Ye et al., 2021).

8.5 Advanced Genomic Frameworks and Breeding Strategies

8.5.1 Pangenomics and Multiparent Populations

Recent advancements in pangenomics are revolutionizing crop genetics by providing a comprehensive view of species-wide genetic diversity, including core and variable genes. This approach aids in identifying key alleles for traits like drought and heat resistance in crops such as maize, wheat, and rice. The use of multiparent populations, like Nested Association Mapping (NAM) and Multi-Parent Advanced Generation Inter-Cross (MAGIC), enhances genetic mapping resolution and supports effective breeding programs (Li et al., 2020). Integrating pangenomics with breeding strategies enables the development of climate-resilient crop varieties and tailored agricultural solutions, contributing to sustainable practices and food security. The creation of super-pan genomes further broadens genetic research by offering insights at higher taxonomic levels, enhancing understanding of genetic diversity across species (Danilevich et al., 2020).

8.6 Integrating Modern Breeding Technologies

Modern breeding technologies, enhanced by high-throughput sequencing (HTS), are transforming crop improvement through genomic selection (GS) and genome editing tools like CRISPR-Cas. CRISPR-Cas systems, originally part of bacterial

immune responses, are now used for precise plant genetic modifications, offering advantages over other editing technologies (Tanny et al., 2023; Yuan et al., 2023). These systems not only restrict horizontal gene transfer in bacteria but also hold promise for plant improvement and the development of biosensors. Research continues on optimizing CRISPR-Cas applications and understanding its interactions with anti-CRISPR proteins.

8.6.1 Genomic Selection (GS)

Genomic Selection (GS) is a modern plant breeding method that uses genome-wide marker data to predict crop performance without extensive phenotypic screening (Jannink et al., 2010). GS streamlines breeding by selecting individuals with desirable genetic profiles based on predictive models (Ahmar et al., 2020). Unlike traditional marker-assisted selection (MAS), GS incorporates all marker information, reducing bias and explaining variance from small-effect quantitative trait loci (QTL) (dos Santos et al., 2022). It accelerates breeding by eliminating repeated phenotyping and leveraging whole-genome data for predicting complex traits, enhancing yield, resilience, and nutritional quality (Hu et al., 2018). Advances in genotyping, sequencing, and statistical computing have improved GS's efficiency and precision in breeding. This method, combined with high-throughput phenotyping and GWAS, offers significant advantages over traditional methods.

8.6.2 CRISPR-Cas Systems

CRISPR-Cas systems have revolutionized genome editing by allowing precise modifications to DNA, such as insertions, deletions, or alterations, with minimal off-target effects (Yang et al., 2021). This technology enhances crop traits like yield, resilience, and nutrition, facilitating the development of high-yielding and climate-resilient varieties (Li et al., 2021). CRISPR-Cas systems have been pivotal in improving crops' resistance to pests, diseases, and environmental stress, contributing to food security and sustainability. They enable the creation of viral-resistant plants and other beneficial traits, advancing gene therapy and crop improvement. Despite challenges in *in vivo* delivery and target design, ongoing research is expanding CRISPR-Cas applications and capabilities (Tanny et al., 2023). The technology is cost-effective and has shown promise in perennial crops and bioinformatics tool development for optimizing experiments (Sharma et al., 2021; Wang et al., 2023).

8.7 Conclusion

This chapter has illustrated the transformative potential of high-throughput sequencing and associated genomic technologies in developing climate-resilient crops. Through detailed case studies, exploration of pan-genomics, and the application of machine learning, it is clear that integrating these technologies into traditional and modern breeding practices can significantly enhance the ability to produce crops that are adaptable, robust, and capable of sustaining agricultural productivity under changing climatic conditions. The continued advancement and integration of HTS technologies in farming practices hold the promise of revolutionizing agricultural productivity and food security globally.

Enhancing genetic gain requires a multifaceted approach, beginning with understanding genetic variance (σ^2_g) by leveraging genomic databases and high-throughput phenotyping to identify and utilize novel alleles and haplotypes. The use of multiparent populations, such as Nested Association Mapping (NAM) and Multiparent Advanced Generation Inter-Cross (MAGIC), significantly improves mapping resolution and statistical power. Optimizing selection intensity (i) is critical for accelerating genetic progress, achieved by expanding population size and enhancing selection accuracy through advanced phenotyping and genotyping technologies. Reducing breeding cycle time (t) is facilitated by Speed Breeding (SB) and genomic strategies like marker-assisted selection (MAS) and genomic selection (GS), expediting trait introgression. Advancing heritability (h^2) estimates through robust experimental designs, precision phenotyping, and complex statistical modeling enhances breeding efficiency. Additionally, highthroughput genotyping and phenotyping using next-generation sequencing (NGS) platforms enable the capture of extensive genetic diversity, integrating genomic estimated breeding values (GEBVs) and genotype $\times$ environment interactions to refine genomic prediction models and improve hybrid performance.

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Chapter 9

Empowering Crops with Nanotechnology for Enhanced Climate Resilience



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9.1 Background

Nanotechnology has garnered significant interest in recent decades because of its auspicious uses in the domains of pharmacology, medicine, engineering, and other professions (Ahmed et al., 2022). Nanotechnology, nanoparticles, and nanocomposites have been recognized as environmentally friendly sectors in nanotechnology businesses (Gupta et al., 2023). Due to their tiny size and unique electrical and optical characteristics, they possess numerous advantages. Their enormous surface energies make them particularly noteworthy and hold great potential for various applications (Mazari et al., 2021). Nanomaterials encompass various nanoscale structures, such as nanoparticles, nanofibers, nanotubes, and nanoplatelets, constructed from multiple substances, including metals, oxides, polymers, and nanocomposites. Their unique properties come from their precise small size, which results in a large surface area and increased sensitivity (Njuguna et al., 2021). Nanomaterials exhibit distinct physicochemical properties compared to their larger counterparts, such as alterations in electrical conductivity, heightened chemical reactivity, increased mechanical strength, and greater adsorption capacity (Barhoum et al., 2022; Khan & Hossain, 2022). These properties could be used in several

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applications, including agro-nanotechnology, which has recently attracted worldwide attention. Many studies have highlighted the use of nanoparticles in agriculture, indicating significant interest in the various benefits of nanomaterials for improving the agricultural sector (Mariyam et al., 2024; Ashraf et al., 2021). The study of the impact of nanomaterials on climate change and agricultural resilience is part of a broader framework where agriculture is increasingly obliged to address concerns related to sustainability and productivity (Rasool et al., 2024).

This literature search aims to enhance comprehension of how nanomaterials might confront these difficulties through novel approaches. The intent is to meet the increasing demand for scientific data to guide decision-making in the face of rapid climate change and environmental challenges. This highlights the physical, chemical, and biological consequences of nanomaterials utilization, providing a comprehensive and nuanced view of how nanomaterials can help transform the agricultural industry to meet the challenges of climate change and crop resilience.

9.2 Climate Change and Crop Impacts

Food security is a significant challenge worldwide as global warming and climate change continue to disrupt agricultural systems (Beddington et al., 2012). The future impacts of climate change on agriculture will worsen an already worrying situation, with nearly 800 million people undernourished, and a 70% increase in food production by 2050 to feed nine billion people, according to forecasts (Van Dijk et al., 2021). Agricultural production depends mainly on temperature and precipitation, the two most important climatic variables (Saifi et al., 2024). Changes in temperature result in changes in the temperature range to which crops are exposed, as well as changes in crop evapotranspiration rates. Fluctuations in rainfall also affect the amount of water available, as well as crop irrigation (Neenu et al., 2013). The growth and functioning of many economically important species will likely be negatively impacted by future climate variability, notably due to rising temperatures (both minimum and maximum temperatures), the variability of rainfall, and the expected increase in the frequency of climate-related floods and droughts (Zhao et al., 2005). These changes pose a high risk to agricultural production, which can lead to reduced crop yields and increased insect pest populations for various crops, which would reduce the quality of crops, food, and human health (Saifi et al., 2024).

As reported by the United Nations Development Programme (UNDP), human activities are responsible for climate change by sustaining global warming through the emission of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and chlorofluorocarbons (CFCs) (Trenberth, 2018). Rising temperatures caused by the greenhouse effect, or global warming, lead to a significant decline in agricultural productivity (Chauhan et al., 2014). According to forecasts by the Intergovernmental Panel on Climate Change (IPCC), global temperatures could rise to 6 °C in the next 100 years, which could have severe consequences for many sectors of the economy. Recent reports indicate that the average annual losses for wheat, rice, and corn could

increase by \$500, \$1000, and \$3000 million if an increase of +2 °C (Tilmes et al., 2020). The primary consequences of global warming arise from temperature rises that exceed the specific temperature threshold necessary for various crops. Elevated temperatures exceeding the threshold lead to decreased photosynthetic levels, reduced chlorophyll concentration, and instability of RNA (Moore et al., 2021). Rising temperature hinders the opening of stomata, affecting gas exchange regulation between plants and the surrounding atmosphere. Figure 9.1 illustrates the notable influence of temperature on the control of stomatal conductance, emphasizing the ideal temperature ranges for various crops. This knowledge is crucial for adapting to weather fluctuations and maximizing agricultural practices.

Raising CO₂ levels can decrease photorespiration and stomatal conductance, whereas higher temperatures can enhance respiration. Simultaneously, the direct consequences of heightened greenhouse gas levels can negate the beneficial impacts of CO₂ on photosynthesis. Heat stress may harm plants' photosynthetic machinery, namely the lipid membrane, oxygen-evolving complex, and soluble processes involved in photosynthesis (Lee et al., 2020; Dusenage et al., 2019). In addition to decreased photosynthesis, high temperatures increase photorespiratory ammonia. This process enhances the buildup of reactive oxygen species (ROS) inside cells, resulting in cellular-level oxidative stress. The regulation of stomata closure by ABA at elevated temperatures is also associated with reduced crop yields (Djanaguiraman et al., 2020; Saito & Uozumi, 2019). Chlorophylls may produce

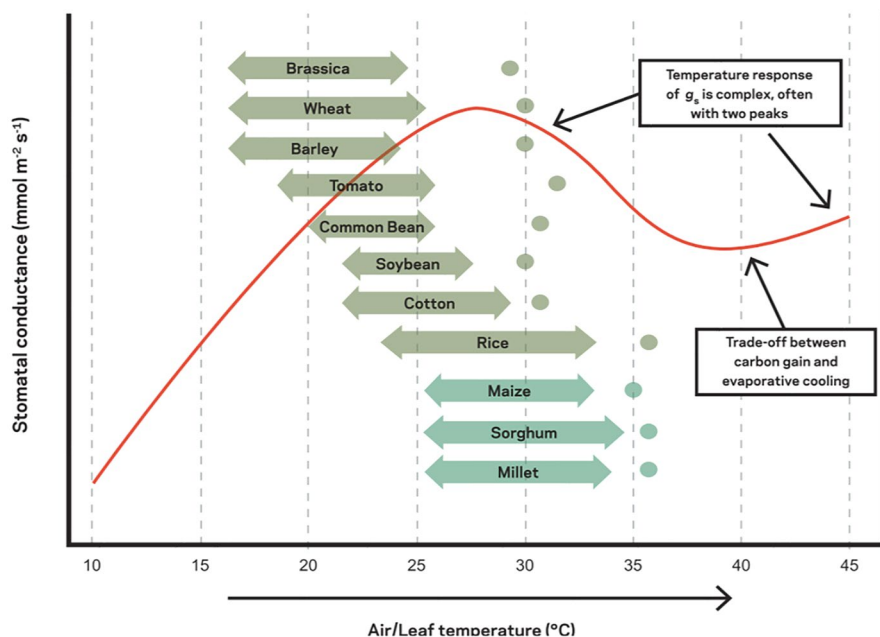


Fig. 9.1 Changes in stomata conductance relative to temperature in different agricultural crops. (Reproduced with modification from Moore et al. (2021), under CC-BY 4.0 license)

harmful reactive oxygen species and excessive energy when they absorb too much light. Drought stress causes a partial closure of the stomata to minimize water loss, decreases the rate of carbon fixation, and can lead to a decrease in the antioxidant defense of plants. Fungal pathogens can produce reactive oxygen species that harm plants, resulting in cell wall degradation and better availability of nitrogen resources. Many biotic and abiotic stress-free radical generators can lead to photooxidation stress in a plant. Extreme environmental conditions related to water and heat are the most damaging factors contributing to these stresses. Water stress is a major environmental problem, particularly in semi-arid and arid areas where agricultural production suffers substantial losses (Suman et al., 2021; Priyan, 2021; Hamilton, 2019). In light of the difficulties presented by climate change, it is crucial to not only address steps to reduce its impact but also to focus on adapting to the resulting consequences to ensure the long-term viability of humanity. This is of particular importance in the agricultural sector, which must implement innovative solutions to ensure food security on a global scale (Anderson et al., 2020). Nanomaterials offer promising solutions to bring about favorable changes to the resilience of agricultural systems, reduce greenhouse gas emissions, promote production, increase crop yields, and promote carbon sequestration and the capture of renewable energies. The basis of their use is their small particle size, which gives them unique properties compared to commonly used, more extensive materials (Ur Rahim et al., 2021). However, additional research is needed to fully understand its long-term impact and improve its integration into agricultural practices.

9.3 Understanding Nanomaterials

Nanomaterials are particles with dimensions between 1 and 100 nanometers, exhibiting unique properties that differentiate them from materials at the macroscopic scale. Nanomaterials may be categorized according to their size into dilute, low-dimensional, dimensionless, one-dimensional, and two-dimensional groups (Salkar, 2020). The manufacturing process of these materials may involve various chemical and physical methods, each with advantages and disadvantages. The process selection depends on the required characteristics, manufacturing circumstances, and production capability (Tulinski & Jurczyk, 2017). Several nanosystems, including carbon, metal oxides, organic, and inorganic systems, are used to enhance the physical and chemical characteristics of materials (Seaberg et al., 2021).

Nanotechnology presents remarkable opportunities in nanomaterial research and business, widespread throughout several sectors, including health and personal care, automotive, electronics, agriculture, construction, and the environment. This signifies a substantial worldwide economic issue (Miyazaki & Islam, 2007). It involves studying and manipulating nanostructures and systems, including their design, characterization, production, and application. These materials, which have distinct features such as their form and reactivity, display notable distinctions from their larger equivalents. Nanotechnology integrates the disciplines of physics, chemistry,

microbiology, cell biology, and catalytic science to enhance the efficiency of nanoscale devices and broaden possibilities for research and development (Assad et al., 2022; Patel et al., 2021).

Current technological advancements allow the creation of smaller and more accurate nanomaterials to reduce the impact of climate change, which we will see in the following section. These nanomaterials consist of nanosensors for monitoring carbon dioxide and methane levels and functionalized nanoparticles and nanostructures to enhance efficiency in the infrared spectrum. Absorbers must possess consistent geometries and predictable measurements. Nanotechnology enables precise prediction of desired outcomes while minimizing the effects on non-targeted organisms (Lowry et al., 2019).

9.4 Nanomaterials for Climate Change

Climate change determines the continuous and long-term changes in temperature, precipitation, wind patterns, effects on atmospheric pressure, moisture levels within the environment, and other aspects of the Earth's climate system (Attri, 2020; Saifi et al., 2024). The rise in temperature factor is the primary concern for the future of the globe. However, nanostructure materials have enormous potential to replace conventional counterparts in an environment-friendly manner and can positively affect maintaining the optimal temperature. Nanosized particles such as nanomaterials have positive biological impacts (Chausali et al., 2021). Nanomaterials also may play a positive role in reducing global warming by absorbing protected environment gases. Various nanomaterials are incorporated into green environments through nanocomposites and polymeric structures used in roofs, windows, and wall coatings. However, their potential toxicity to the environment, including adverse effects on photosynthesis, transpiration, nucleic acids (Rasool et al., 2019), and human health, remains a significant concern (Khan et al., 2019).

Environment and agriculture effects such as biodiversity loss, coastal flooding, localized flooding, heat stress, marine ecosystem damage, pathogen spreading, insect movement, quality and quantity of crop yield, and other effects like heat-induced mortality, pressures on mental health, etc. have been impacted negatively due to the climate change (Chausali et al., 2023). Nanotechnology has provided sustainable alternative solutions for combating climate change effects and securing a safe environment (Perri et al., 2017). For instance, Khan et al. (2017) postulated, based on their own research and related studies, that nanoparticles can enhance plants' adaptation and tolerance to stress by stimulating defense mechanisms and the expression of stress-related genes, reinforcing the immune system of plants to several abiotic stresses. In addition, nanoparticles improve the germination power of the seeds of plants belonging to the Fabaceae family, such as soybean, being under water stress (Sedghi et al., 2013). Green environment, wastewater treatment, biofuels, monitoring, etc. are several applications of nanomaterials in combating climate change (Fig. 9.2) (Chausali et al., 2023). Nanomaterials are essential in

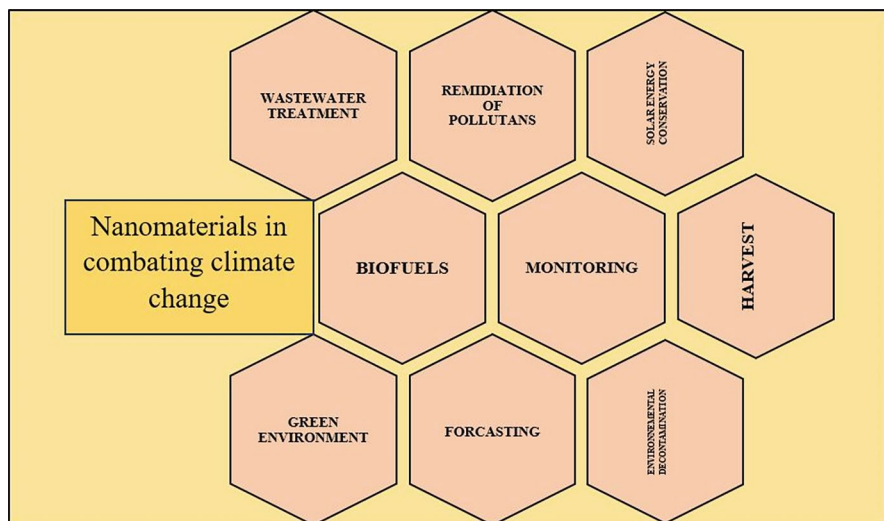


Fig. 9.2 Role and several applications of nanotechnology in combating climate change

addressing climate change in agriculture by promoting increased yield, chlorophyll content, and gene expression in plants. They enhance drought tolerance by increasing root hydraulic conductivity and water uptake while signaling various proteins involved in oxidation-reduction, stress signaling, and hormonal mechanisms. Due to their high mobility, nanoparticles facilitate the efficient transport of nutrients to all plant parts. Nanomaterials help combat climate change by improving agricultural productivity and resilience. They help plant growth, increase drought tolerance, and raise nutrient efficiency, contributing to more sustainable farming practices and better adaptation to changing climate conditions (Kumari et al., 2022).

Nanoparticles are valuable tools in referencing environmental threats posed by climate change. They can extract carbon from the air, remove dyes from water, and process sludge from waste. Furthermore, nanomaterials are being engineered to efficiently capture carbon dioxide from the atmosphere, remove toxic pollutants from water, and convert solid waste into valuable products (Paramsothy, 2020). These advancements highlight the potential of nanotechnology in promoting environmental sustainability and mitigating climate impacts. The use of nanomaterials represents a highly promising new strategy that has great potential to positively influence the growth and nutrition of plants and their protection against diseases, pests, and other adverse environmental conditions, which is achieved with the use of nanoparticles in plant tissues and seeds as an advanced and sustainable method with few risks in agriculture (Ioannou et al., 2020).

Many environmental applications of nanomaterials have recently been concentrated on the water sector, such as the extraction of hazardous organic compounds, particularly chlorinated aromatics, remediation of heavy metals, purification of drinking water, and desalination of seawater (Kharisov et al., 2014). Heavy rainfall

and its associated catchment processes disturb the nitrogen, carbon, and water cycles and pollute freshwater bodies. In addition, many factories and industries release toxic and carcinogenic waste into nearby water bodies and landfills. These long-lasting pollutant compounds accumulate in groundwater and soil, and their residues are often found in the tissues of living cells (Held & Soden, 2006). Nanomaterials could play a key role in environmental restoration by addressing climate change, aiding in the breakdown or degradation of pollutants, capturing harmful water contaminants, and converting greenhouse gases into fuels (Thongam & Chaturvedi, 2021). Nanomaterial applications have also reached the food industry sector by safely transporting food products without compromising taste, nutrition, and quality. In addition, it also inhibits contamination and maintains the mechanical, physiological, physical, and chemical characteristics of food products (Chausali et al., 2022). Moreover, nanomaterials contribute to the advancement of renewable energy. They are used to develop more efficient solar cells, batteries, and fuel cells, promoting cleaner energy sources and reducing dependence on fossil fuels. Nanotechnology also improves energy storage, transformation, and conversion processes and possesses chemical durability, making renewable energy systems more sustainable and efficient (Cheriyamundath & Vavilala, 2021). Nanomaterials are becoming recognized as potent adversaries in the battle against climate change, providing inventive solutions across several industries. In agriculture, nanoparticles enhance seed germination and promote plant development, as previously stated (Aslani et al., 2014), increase yields, and enhance drought tolerance by increasing root hydraulic conductivity and water uptake. They also stimulate the expression of stress-related genes and defense mechanisms, making plants more resistant to abiotic or biotic threats (Van Aken, 2015). Nanomaterials possess unique characteristics such as catalytic activity, sensing capabilities, high aspect ratio, hydrophobic and hydrophilic properties, and electrostatic interactions. These attributes enable them to play a crucial role in addressing climate change and enhancing water purification by offering innovative and sustainable solutions (Devi & Chaturvedi, 2021).

9.5 Nanomaterials for Crop Disease Control

Nanotechnology holds significant potential to transform agriculture and the food industry by introducing innovative tools to optimize inputs and outputs and enhance sustainability. It has potential applications in plant protection through the on-site monitoring of pests and diseases. It also helps boost crop productivity in sustainable crop production management (Baker et al., 2019). Ojha et al. (2018) revealed a concept of *minimal usage with maximum effect* describing that nanotechnology has been utilized as an advanced strategy for crop protection and the maintenance of long-term agricultural sustainability. This concept focuses on using tiny amounts of nanomaterials to impact crop protection and sustainability positively. This advanced approach leverages the unique properties of nanoparticles to improve various

aspects of agricultural practices, including pest control, nutrient delivery, and disease management while minimizing resource usage and environmental impact. Another critical issue is the extensive use of chemical fertilizers and pesticides in agriculture, which has significant environmental repercussions. Kaningini et al. (2022) reported that up to 90% of the chemicals applied for crop disease control are inadvertently released into the environment during application. This inefficiency leads to widespread pollution, impacting both soil and water quality.

Meanwhile, the ongoing use of pesticides and fungicides in agriculture poses significant health risks due to the accumulation of toxic chemicals in food products. This contamination affects plant and human health and the broader food chain (Munir et al., 2023). Therefore, agricultural systems need to integrate sustainable modern technologies to effectively manage crop diseases and improve crop production (Kumari et al., 2023). In this context, nanotechnology represents a promising approach for enhancing food security and sustaining plant health. Nanotechnology indeed holds significant promise in revolutionizing agricultural practices, and it has the potential to exceed traditional methods in crop production. Nanomaterials can significantly enhance several facets of crop production, including soil health, seed germination, crop growth, gene expression, ecological sustainability, and plant stress tolerance (Khan et al., 2021). These benefits highlight the potential of nanotechnology to create more sustainable and efficient agricultural systems.

Owing to their diminutive size, ease of transport, high efficacy, and prolonged stability, nanoparticles have become the preferred choice for agricultural applications relative to conventional methods. The high efficiency of nanoparticles supports their extensive use in plant pathology, as they offer both environmentally friendly and effective management of crop diseases. In this regard, nanotechnology offers significant potential to aid agriculture and address ecological challenges by developing and applying nanopesticides against plant diseases (Hazarika et al., 2022). Pesticides developed according to nano-based formulation techniques are called nanopesticides (Fig. 9.3).

According to Djiwanti and Kaushik (2019), nanopesticides represent a growing area of research and development that addresses challenges associated with conventional pesticide use. They are potentially less toxic, and therefore, nanopesticides are sustainable and environmentally friendly alternatives for agriculture. Nanopesticides are formulated through various methods, either by using nanoscale particles of pesticide-active ingredients or by employing nanostructured molecules that possess pesticidal properties. Nanopesticides offer significant advantages in agriculture. They improve the dispersion and wettability of formulations, which helps reduce organic solvent runoff and unwanted pesticide movement. Moreover, their remarkable pesticidal activities allow for effective pest management with lower quantities of pesticide, thereby reducing the overall pesticide load on the environment (Islam, 2020). This dual benefit makes nanopesticides a promising innovation in sustainable agriculture.

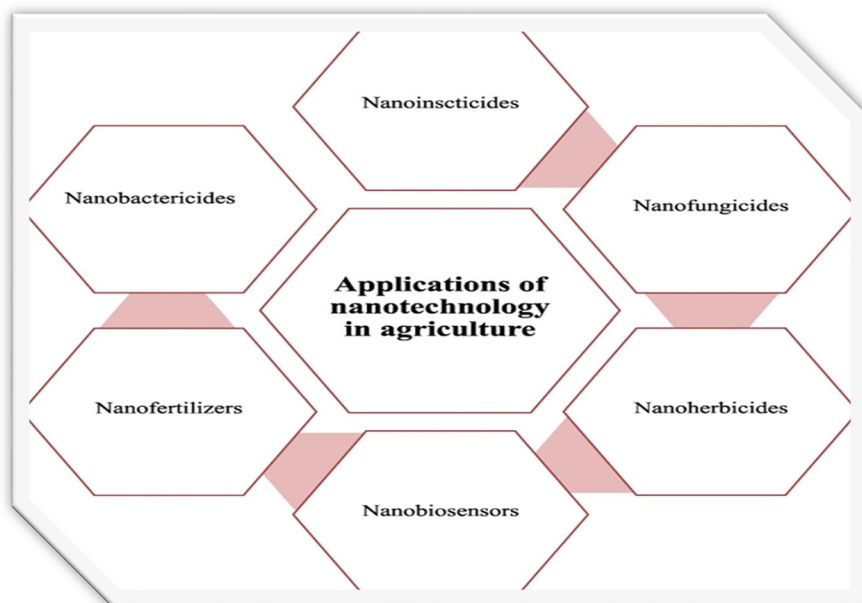


Fig. 9.3 Applications of nanotechnology in agriculture. (Reproduced with modification from Hazarika et al. (2022), under CC-BY 4.0 license)

9.6 Resilience and Sustainability in Agriculture

Climate change is a pressing global issue. Indeed, it has widespread and multifaceted impacts that extend across all nations and sectors. Among the most significant of these impacts are those on agriculture, affecting food security, economic resilience, livelihoods, and population health (Baraj et al., 2024). Climate change has significantly impacted weather patterns globally, resulting in an increase in the frequency, intensity, and duration of extreme weather events. In order to mitigate the potentially catastrophic effects of climate change on susceptible rural populations, it is imperative to use sustainable agricultural practices to adapt to climatic challenges and bolster ecosystem resilience. Sustainable agriculture ensures that ecosystems can maintain their capacity to provide critical services to society (El Chami et al., 2020). While agricultural sustainability has been a guiding principle for several decades, agricultural resilience has emerged more recently as a critical concept, particularly in response to the rising frequency and severity of global issues, including climate change (Volkov et al., 2022). Both concepts are now seen as complementary, with resilience being an essential component of achieving overall sustainability in agriculture.

Indeed, intensive traditional agriculture and climate change have caused substantial ecological damage and present major threats to global food security. In this context, nanomaterials offer promise for facilitating this transition by mitigating

environmental impacts, enhancing agricultural productivity, and reducing contamination (Ur Rahim et al., 2021).

9.7 Contributions of Nanomaterials to Agricultural Resilience

Nanotechnology can revolutionize agriculture by opening up new prospects, like manufacturing nanosensors, to protect food from pests and pathogens. It offers transformative possibilities for agriculture by enhancing pathogen detection and control of increasing incidence of its attack due to climate changes. Advanced agricultural practices might be developed by integrating nanotechnology with genetic engineering and molecular biology (Younas et al., 2021). Therefore, the research on nanomaterials and nano-agrochemicals has made significant progress over the past decade, leading to novel applications in pest management, plant growth stimulation, and soil quality improvement. Indeed, nano-agrochemicals leverage nanotechnology to improve the efficiency and effectiveness of traditional agrochemicals. For instance, Thabet and Alqudah (2024) described that nanoparticles could engage with plant processes at the molecular level, which can affect plant growth, development, and response to stress conditions. Zhang et al. (2024) have described that these nanomaterials offer significant potential for agricultural applications due to their unique properties and functionalities, including inorganic (e.g., silica, copper, iron, zinc, selenium), organic (e.g., (bio) polymers such as chitosan, lipids, proteins, and peptides), and hybrid materials. For instance, iron oxide nanoparticles have shown potential in enhancing plant performance under drought and stress conditions. Iron oxide nanoparticles hold promise for improving water use efficiency and chlorophyll content of different crops under drought stress, potentially contributing to more resilient agricultural practices in the face of climate change.

Similarly, zinc oxide nanoparticles have garnered attention for their potential to enhance plant tolerance to salinity and various abiotic stresses. Zinc oxide nanoparticles strengthen the tolerance of cultivated crops to salinity stress by boosting the plant's antioxidant enzyme activity. This leads to its improved protection against oxidative damage and better overall plant health conditions (Manzoor et al., 2023; Singh et al., 2017). These advancements illustrate the potential of nanotechnology to revolutionize agriculture by making it more sustainable and efficient. Therefore, nanoparticles offer promising benefits for enhancing plant growth and stress tolerance; careful consideration of their concentrations, types, and long-term impacts is essential for sustainable and safe agricultural resilience.

9.8 Challenges and Future Perspectives

Nanoparticles manage several environmental issues and reduce the time and investment required by specific sectors (Kanchi, 2014). In environmental remediation, nanoparticles effectively capture carbon dioxide from the atmosphere, remove dyes and toxic pollutants from water, and facilitate the processing of waste materials. These capabilities not only help reduce greenhouse gases but also mitigate water pollution and more efficiently manage solid waste. Although nanomaterials may pose toxicity risks to aquatic life and ecosystems when released into water bodies (Held & Soden, 2006), their unique properties and multifunctionality make them highly effective for water treatment. They offer significant potential for efficiently removing organic pollutants, microorganisms, and metal ions from water (Bhat et al., 2022). Nanotechnology has been applied in agriculture in various ways, including through the use of nanofertilizers, nanopesticides, and nanobiosensors. For instance, Kah et al. (2018) demonstrated that nanofertilizers have a high efficacy gain compared to conventional fertilizers, revealing that the application of nanofertilizers contributes to a future sustainable agriculture by enhancing crop yield and quality while lowering production costs. In addition, nanofertilizers improve crop metabolism (Rico et al., 2011), and also increase growth rate of some Fabaceae plants such as soybean (Liu & Lal, 2014). Nanostructured materials, including clay minerals, hydroxyapatite, chitosan, polyacrylic acid, and zeolite, are utilized in the formulation of fertilizers for soil and foliar applications. The high mobility and reactivity of nanomaterials enable the efficient transport of nutrients and other essential elements within plants and other systems. This property is particularly useful in agricultural applications, where it ensures that nutrients are effectively distributed to all parts of the plant, improving overall health and productivity. The extensive surface area of hydroxyapatite and its strong affinity for urea facilitate the gradual release of nitrogen from urea (Kottogoda et al., 2011). On the other hand, nanopesticides play a crucial role in effective integrated pest and disease management by targeting a wide range of insects and pathogens through mechanisms distinct from conventional pesticides, enhancing their overall efficiency (Kah et al., 2019). In principle, they have the potential to minimize the use of chemical-based products. Nevertheless, nanopesticides can cause health problems (Ragaei & Sabry, 2014) due to their tiny size; they are easily absorbed and can pass through cell membranes. Also, it can cause lung problems and move to the brain. Furthermore, the durability and reactive nature of some nanomaterials present environmental concerns, compounded by the lack of understanding regarding how to measure environmental exposure to these materials (Usman et al., 2020). This is because of their toxicity, one of the main issues of nanomaterials that threaten the environment and humans (Gardner & Dhali, 2014). Likewise, some of the properties, such as dimension, shape, and reactivity, are important for nanomaterials, but they can also disturb biodiversity or other living organisms (Eldessouky & Ali, 2021). Therefore, partnerships between scientific institutes or universities are vital for investigating diverse applications of nanomaterials. These collaborations are key to creating efficient,

multifunctional, durable, cost-effective, and eco-friendly nanomaterials, while also reducing potential human health risks.

9.9 Conclusion

Nanomaterials can help improve the growth and yield of agricultural plants, depending on the plant species. So, this makes their use require research and complete investigations in the screening and optimization of nanomaterials for different plant species. Adjusting the property and stability of nanomaterials is very important in adapting their efficiency and behavior. Most nanoscience studies on agriculture rely on experiments conducted under controlled conditions, while there is a lack of data on their application in the field. Studies at the field level would be beneficial for the large-scale application of nano-based strategies (Usman et al., 2020). Nanotechnology has a great opportunity to make agriculture more productive and innovative by using nanoparticles and can positively influence the change of climatic conditions. Nanotechnology leverages nanofertilizers, nanopesticides, and nanofungicides to enhance agricultural productivity, ensuring both maximum yield and improved quality. In addition, nanoparticles also play an essential role in soil improvement and plant growth and development (Sarkar et al., 2022). Nanomaterials are undoubtedly key and promising elements in the fight against climate change, but thorough and in-depth exploration by future researchers is necessary. The challenge and perspective for future researchers may be extended in developing efficient processes that use minimal amounts of nanomaterials, creating economically applicable strategies for their synthesis, and integrating the real advantages of this innovative science into everyday life (Teotia et al., 2023). To conclude, integrating nanomaterials into various environmental and energy systems is an important step forward in combating climate change. By improving agricultural resilience, enhancing renewable energy technologies, and providing solutions for pollution control and waste management, nanomaterials hold great promise for creating a more sustainable and resilient future.

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Chapter 10

Crop Genomics for Climate Resilient Agriculture



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10.1 Background

It is crucial to advocate for laws and regulatory frameworks that provide support. Governments and policymakers have a crucial role in encouraging sustainable agriculture practices and the uptake of climate-resilient technologies.

Finally, it is crucial to invest in capacity building and education initiatives to provide farmers with the necessary information and skills to properly use climate-smart farming approaches. Enhancing the farmers' capacity through training and education enables them to effectively respond to climatic problems and embrace sustainable farming techniques. Nowadays, our world is facing many stressing problems that threaten its food security. The most important of them are the steady raise in its population as well as the fact of climate shift. This latter encompasses variations and shifts in weather-related factors such as ambient and soil carbon dioxide level, temperature, humidity, and precipitation. The unfavorable impacts of the change in these factors are leading to gradual global warming, altered precipitation, and elevated CO₂. These adverse effects may expand to comprise other weather extremes in terms of droughts, heat waves, wildfires, floods, and storms. Admittedly, changes in all such factors can greatly affect biological and ecological parameters linked to the cultivated crops. For instance, they may engage the changes in rainfall distribution patterns and generally decreased precipitation that destabilize our general trend for durable agriculture. Clearly, drought takes place more frequently which adversely affects both cultivated soil health and crop yields. It is considered as one of the most damaging factors that call for climate resilient plant phenotypes. About 40% and 21% of maize and wheat production has declined, respectively, from 1980 to 2015 due to climate change in terms of drought (Yuan et al., 2023). Also, the resulting drought is anticipated to globally decrease crop yield in one-half

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of the arable area in the next 50 years. Rising in temperature is another stressing factor of climate change. Bein et al. (2020) reported that the global Celsius temperature has elevated by 0.85 °C in the last 30 years. Samset et al. (2020) stated that such an elevation in atmospheric temperature is ongoing with an assessed rise by 0.2 °C per decade. Asseng et al. (2015) speculated that a 1 °C rise in temperature will lead to reduction in wheat yield by 6% globally, with linked societal effects from the diminished yield of such a key staple crop. For further prediction in global productions of main economic key crops, detailed figures are being assessed. Crop yields will be lowered due to the negative climatic changes by an average of 3.1% in soybean, 3.2% in rice, 6% in wheat, and 7.4% in maize for every global raise by one degree Celsius in its average (Yuan et al., 2023).

These consequences of climate shift will expand to the harmful activities of pests as well. Fruit flies of tropical regions are breaking into unexpected zones due to the changing climate. Gutierrez et al. (2021) reported expansions of the attacks by these flies to temperate regions found in Europe and USA with terrible impacts on fruit production there. The damaging activities of pathogens are also spreading under changing climate as numerous pathogen-host interactions are influenced by altered weather factors. An increase in the systemic infection rate of Turnip mosaic virus on cabbage has already been recorded due to the rising temperature (Yuan et al., 2023). In addition, positive and/or negative influences of climate shift on subterranean and rhizospheric organisms associated with these plants may reflect big impact on agriculture; e.g., the extensive effect of global change in future climate on plant-nematode interaction continuum will cover the abundance, distribution, biogeographic range, reproduction, survival, fitness, and parasitic capacity of the plant-parasitic nematodes (PPNs) (Dutta & Phani, 2023). For such plant-linked organisms, the outputs of climate change may involve several factors with both favorable and unfavorable impacts on them too. Generally, such impacts are based on adaptability of the species, their geo-spatial dispersion, and inherited traits. On the other, climate change is linked to accelerated land degradation, especially soil salinization. Eventually, such various, already introduced or predicted, impacts of climate shift on the food and key crops as well as arable soil health necessitate urgent actions. These latter should be based on boosting the resilience and yields of the target crops for better adaptation of the new/upcoming climate (Viswanathan et al., 2020).

This chapter addresses the influences of climate change as a whole deal resulting from the emission of greenhouse gases and leading to lowering of crop yields. Consequently, its main focus is on crop genomics as promising factors for climate resilient plant genotypes. However, it is well known that all plant characteristics (phenotypes) are the outcome of the interaction of its genetic makeup (genotype) with its environment. Although the chapter title addresses the former part (genetic constitution) of a plant, some environmental practices that help combat climate change will be added herein as examples to optimize climate resilient plant phenotypes. Furthermore, it should be clear that while shifts in most relevant environmental factors will degrade plant growth/yield parameters, other factors included in climate change may act in counter direction. Obviously, because the climate shift

impacts will differ due to various spaces and times, it is perceivable that the plants and their relevant organisms will react/adapt according to their species specificities and settings. For instance, following the aforementioned example of the nematodes, climate change will worsen crop damage caused by PPNs by stretching abundance and distribution of these nematodes. On the contrary, other PPNs-related parameters such as entering cryptobiosis and sex reversal will act in opposite trend (Dutta & Phani, 2023). Nonetheless, major negative consequences will prevail due to the unusual shifts in climate-related key factors.

Crop resilience reflects the potential of the plant to recover from, or at least withstand, the impacts of unfavorable climate shift. Hence, numerous key production practices may serve to adapt cultivated crops to the change. Such practices may comprise but not limited to in-situ moisture maintenance, manipulating organic carbon build up in cultivated soil, incorporation of soil amendments instead of destroying useful plant residues, recycling water for supplemental plant needs, using resistance/tolerant cultivars/varieties against the prevalent adverse biotic and abiotic factors, fortifying pathogen and pest control to boost crop productivity. The related techniques may involve utilizing sequential, dual-purpose, and/or co-application of farming inputs, and locating specific nutrients for optimum agronomic and horticultural management (Abd-Elgawad, 2021; Singh Bakala et al., 2021).

Such farming practices do not negate an imperative need to complementary approaches that are related to utilizing sophisticated plant breeding for new genotypes and developing current crop cultivars/varieties to cope with climate change. Obviously, a genetically modified (GM) or genetically engineered food/crop always possesses an ingredient that is brought on by a plant with a shifted genetic composition. Although many of processed foods/crops in developed countries such as USA have at least one GM ingredient, numerous consumers seem reluctant to the use of GM crops/foods. Hence, novel plant breeding technologies (NPBTs) have currently appeared as alternative techniques to accelerate the introduction of desirable/improved traits. These NPBTs can involve precision genome-modulating devices; e.g., transcription activator-like effector nuclease (TALEN) techniques and the clustered regularly interspaced short palindromic repeat (CRISPR)/CRISPR-associated protein (Cas) methodologies (Zaidi et al., 2019). Admittedly, these approaches should be utilized with an end in view to enhance safe productivity and back security of food worldwide. The new era of plant breeding should also incorporate recent methods of crop genomics for climate resilient plant phenotypes. In this vein, additional and related techniques such as gene editing, targeted gene silencing, and relevant bioinformatics are emerging tools that could lead to rapid progress in optimizing farm management and remodeling cropping systems with climate change. Moreover, PCR-based approaches to examine multitrophic interactions among pests, plants, diseases, and their biocontrol agents can be harnessed to boost crop production and diminish such undesirable ecological impacts.

10.2 A Brief on Current Limitations and Solutions for Boosting Crop Productivity

Although boosting both production exercises and breeding of many crops have backed their quantitative and qualitative yields globally, the world population growth is at a faster pace than these yields. This issue is being aggravated especially at developing countries. Factually, 9.4 billion tons were gathered as food crops in year 2019, which represent 53% increase relative to that in year 2000 (FAO, 2021). This latter reported also more than a double increase of vegetable oil in the last 10 years. However, such increases have mostly been attributed to the application of both pesticides and fertilizers (Yuan et al., 2023). Therefore, there are physical limits to this increase due to excessive use of fertilizers and societal limits ascribed to environmental pollution and health hazards linked to many chemical pesticides. Recent improvements in crop yields were centered on pest/pathogen control, nutrient supplements, use of pesticides, and occasionally on developed water irrigation regimes. The FAO (2021) annual report indicated that the global land furnished with such irrigation regimes was raised by 342 hectares in year 2019. The same report recorded that pesticidal application was intensified by 36% more in year 2019 than 2000. Thus, it is logic to assume that getting further increases in using these pesticides and fertilizers will be continuously more challenging than ever.

Another type of limitations is relevant to the diminished genetic diversity of plant species resulting from intensive selection and domestication of economically key crop genotypes. While these genotypes have been bred for the best yield in certain settings, some abiotic and/or biotic stress tolerance has been lost as a trade-off for the attained boosted yield. Moreover, the classical breeding usually needs seasonal phenotypic selection and is time-consuming. Therefore, growing alternatives are desperately required as promising solutions to expedite the generation of climate-smart crops. Generally, genetic refinements via classical selection will go on not only as basics but also because the related breeding techniques require less expertise and are cost effective (Anand et al., 2023). Nonetheless, transgenic plants have turned to be fairly common, and they are authorized for genetic reforms that distinctly are not possible with classical breeding (Baiocchi et al., 2017). To name but a few, ongoing studies are trying to identify better resistance sources against pests and pathogens under controlled conditions. They could, for instance, compare biochemical and molecular markers for reliable and swift screening of root-knot nematodes (RKNs), species of the plant-parasitic genus *Meloidogyne*, for resistance in tomato plants. Abd-Elgawad (2020) confirmed that such recently identified resistant genotypes may be utilized further in *Meloidogyne* spp.-resistance breeding plans as the *Mi23* marker can be exploited for quick and effectual sifting of the germplasm. Such resistance genes can be transferred via genetic engineering tools to other crops. This is especially important for livestock-feeding crops that cannot benefit from toxic nematicides because animals feed on all their foliage. Clearly, many forage legumes are highly susceptible to *Meloidogyne* spp. infection with considerable losses (Baltensperger et al., 1985). In contrast, a few factors such as

virulent RKN populations and high temperatures can break the resistance (R) gene where plants become susceptible. So, plant breeders would better employ several R genes or quantitative trait loci (QTLs) than a single gene to avoid these defects (Abd-Elgawad, 2022a). Ultimately, generating climate-smart crop cultivars and varieties together with upgrading novel crop management tactics and strategies should be harnessed to circumvent bad consequences of climate change.

10.3 Genomics-Aided Climate Resilient Plant Genotypes

Genomics-aided breeding can cut short the processes needed for phenotypic analysis in plant breeding, given the above-mentioned demerits of classical phenotypic selection. Such plant breeding approach can hasten the production of elite crops via the sophisticated genotyping technology based on recent DNA sequencing (Yuan et al., 2023; Abd-Elgawad, 2023a) or, more generally speaking, molecular biology-based technology.

10.3.1 *Utilizing Progressed DNA Sequencing for Climate Resilient Plant Genotypes*

Admittedly, harnessing of evolving high-throughput DNA sequencing of many plant species has greatly benefited its usage in crop genomics. Additionally, contrary to short sequence reads and related issues (Wang & Wang, 2023), complete genome sequencing is being progressively used implying the detection of single nucleotide polymorphisms (SNPs) and structural dissimilarities in addition to the linkage of such dissimilarities with heritable agronomic attributes (Bayer et al., 2021). Obviously, current progresses in long-read DNA sequencing and relevant technological tools have reinforced the generation of various assemblies for sober-quality chromosome measure genomes. The emerging technologies of long-read DNA sequencing such as Oxford Nanopore and Pacific Biosciences (PacBio) methods are undoubtedly superior to short read ones in terms of their accurate identification of structural variants especially when complex genomic sites are complicated (Gutierrez et al., 2021). The two initiatives set by Wenger et al. (2019) for PacBio HiFi sequencing and Sereika et al. (2022) for Oxford Nanopore R10.4 sequencing have further enhanced the reliability of variant characterization and genome assembly. Moreover, genome assemblies could be surely generated at a high chromosomal grade aided by relevant technologies. Such technological examples may include optimized optical mapping (Yuan et al., 2020) as well as the sophisticated chromosome conformation capture approaches. The latter high-throughput approaches may also comprise Oxford Nanopore Pore-C and Dovetail Omni-C (Deshpande et al., 2022). Haplotype-analyzed genome may be produced for

outcrossing species as well (Zhang et al., 2020). On the other, the use of RNA sequencing can set quantitative measure of genetic transcripts in the targeted plants. Stark et al. (2019) confirmed that such outputs allow examining plant-cellular reactions to different stresses; e.g., heating, drought, and cold. Thus, better grasping of biological processes related to these reactions could be gained. Having sequenced RNA, differentially expressed genes in plants under specific conditions could be easily identified. With advances in long read-RNA sequencing, Oikonomopoulos et al. (2016) proved that the whole messenger RNA could be captured once one single molecule was read. Consequently, formerly unclear mapping was clearly read for data analysis with sound capture of various transcript isoforms. Concerning single plant cells, individual-cell RNA sequencing is being used in plants in order to differentiate and produce the required data, e.g., detecting cell types and examining expression of single-cell gene. Furthermore, gene expression could be better understood by setting cell types to the expressed gene positions via spatial transcriptomics (Williams et al., 2022). Hence, RNA sequencing can possess a key role in characterizing genes linked to biotic/abiotic stresses (Yuan et al., 2023). Finally, such modern technologies can offer insights into different aspects of plant biology and physiology that must be a way forward in the breeding of optimized crop genotypes for climate resilient plant genotypes.

10.3.2 Sophisticated Genotyping Technology

It is necessary for scientists to supplement the above-mentioned high-throughput sequencing by progressively adjusted phenotyping for genomic-based breeding. In order to facilitate the downstream linkage between genotypes and phenotypes for perfection of plant breeding, it is imperative to accurately and efficiently collect all required phenotypic data. However, conventional collection of phenotypic data requires many efforts, while biases and errors can occur during the handwork evaluation of phenotypes. Danilevicz et al. (2022) evidenced that efficient and extensive collection of phenotypic data can be boosted via high-throughput approaches and phenotypic platforms. Absolutely, phenotyping data requires many relevant aspects such as plant cultivation, growth, development, and yield; crop biomass and architecture; and photosynthesis. Also, additional data closely related to climate change are required and may comprise tolerance to heat, drought, pests, pathogens, flood, and other stressors (IPPC Secretariat, 2021). Occasionally, reporting and monitoring of such data are so big that they address hundreds/thousands of plants at once. Therefore, developing image-based phenotyping can offer a functional technique to grade the reaction of crops to various climate-related stressors. Humplik et al. (2015) could effectively use an image platform to report chlorophyll fluorescence found in pea plant. Utilizing relevant tools/devices, such as satellites, drones, and smartphones, has enabled a wider scope of image capture to observe the crop development (Yuan et al., 2023). Others (Kolhar & Jagtap, 2023) reported cameras and

sensors as devices in order to capture different characters useful in plant breeding such as the water use efficiency, plant height, flowering time, and yield.

Moreover, various approaches via artificial intelligence and its related devices may help to elucidate image data for decision-making. These approaches may involve machine learning algorithms and deep learning to obtain the required information. Employing such tools along with certain models could soundly interpret and predict breeding-related data (Danilevicz et al., 2022). In plant phenotyping, Yuan et al. (2023) reviewed a few methods of deep learning applied for different plant species with successful and superb results. For example, accuracies of 95.91% and 99.66% for spike and spikelet counting, respectively, were attained using a classical neural network (CNN). Also, a CNN-long short-term memory framework was effectively applied to examine the dynamics of plant growth for temporal phenotyping, with 96% accuracy in the framework. Further deep learning applications engaged plant phenotyping investigations such as measuring stresses on plant leaves induced by pests/pathogens as well as fruit and yield evaluation. Merging genome-wide association studies (GWAS) with sophisticated phenotyping facilities, phenomics can be advanced as new tools to examine genetics/genomic characterization for increasing the breeding efficiency of plants under climate change conditions (Yang et al., 2014). Factually, deep learning is being extensively utilized to examine and explicate big data of further phenomics in order to facilitate ecological stress phenotyping (Singh Bakala et al., 2021). Therefore, it is anticipated that deep/machine learning will continue to advance plant phenotyping as more new algorithms are evolved. Finally, such tools are expected to assist in the assortment of genotype-to-phenotype linkage and genomics-aided breeding.

10.3.3 Complementary Approaches for Genomics-Assisted Breeding

Genomics-aided breeding can merge the statistics and details from huge phenotypic and genomic data to identify/characterize genetic markers, key genes, QTLs, chromosomal alleles, and/or haplotypes. Thus, these tools and data are able to breed wanted crop cultivars/varieties via genomic selection, marker-assisted selection, and advanced genetic engineering (Scheben et al., 2017a). Genotypes and phenotypes closely linked to climate resilience could be smoothly acquired through developing high-throughput phenotyping and DNA sequencing (Bayer et al., 2021). Clearly, genomics-aided breeding is running through tools that bode well for boosting crop productivity during climate change.

10.3.3.1 Use of Biochemical and DNA Markers As Well As Genetic Variation

Such markers are heritable and amply found throughout plants-genetic structures. Therefore, Abd-Elgawad (2022a) stressed the need to expand the utilization of marker-assisted selection (MAS) technique to select the required character of plant phenotype. Simply, they can lead to identify the target genes that help in plant breeding. Contrary to MAS, genomic selection (GS) utilizes markers of genome-wide DNA with an end in view to foretell the genetic benefit of individual breeding for complex attributes such as various components that form a crop yield (Singh Bakala et al., 2021). Recognition of genetic markers is necessary to carry out sound analyses; e.g., QTL analysis and linkage mapping as well as relevant association investigations. On the other, Abd-Elgawad (2023a) speculated that using transposon mutagenesis can possess not only mutations with higher frequency and less lethal efficacy on the target organism, but it may also incorporate such markers into constructions of entomopathogenic nematode (EPN) strains and recover desired genes after mutagenesis to obtain more effective EPNs for biocontrol of serious plant pests and pathogens (Abd-Elgawad, 2017; Askary & Abd-Elgawad, 2021). Despite the big genetic variations among them, EPNs and other biocontrol agents (BCAs) are usually more sensitive to biotic/abiotic factors in their settings than chemical pesticides. This case lends top-priority to quantify spatial (temporal and geographic) distribution patterns of crop pests/pathogens and their BCAs under climate change. Obviously, quantification of such variables has proved to foster sound pest-management decisions (Abd-Elgawad, 2023b) and improve plant protection strategies for sustainable agriculture (Abd-Elgawad, 2024).

Also, identifying and characterizing genetic variations via genotyping by sequencing (GBS) has been progressively utilized as it offers labor savings and possesses fast, high-throughput results. Different GBS techniques have been evolved for studying crop genomics. These techniques can generally be classified into two divisions: entire genome resequencing and diminished representation sequencing (Scheben et al., 2017a). Scheben et al. (2017b) reported that the sequencing coverage of both divisions is usually low ($<1\times$) reflecting the fact of inexpensive-related processes. Moreover, as SNPs are so heritable and amply distributed within the plant genome, they can ease the evaluation of phenotypic and genotypic links while using GBS (Scheben et al., 2017a). For instance, 459,304 SNPs found in 10,323 sorghum-genetic constitutions were characterized where these SNPs were enriched in both genic regions and arms of sub-telomeric chromosome (Hu et al., 2019). Contrary to GBS, whole genome sequencing (WGS) can get the best of certain restrictions of GBS; e.g., PCR duplications and allele dropout as well as identifying more variations. These latter may involve gene presence/absence variations and structural variations (Yuan et al., 2023). Updated studies revealed the sound effect of structural variations in shifting the phenotypic variations in individual plant species. Certainly, WGS is more expensive than GBS. Yet, WGS has high resolution in detecting variations which may allow for

comprehensive decoding of the relations between genotypic and phenotypic characters; offering great help in breeding.

10.3.3.2 Supragenome and Graph Genomes

As supragenome (pangenome) refers to all set of genes found in all strains related to a clade, this term indicates the entire genic content of a plant species too. In order to swiftly and effectively address such sets of genes, we should utilize bioinformatics that can bolster the assembly production of high-quality genomes. That is because assemblies of different genomes related to one species cannot be captured by an individual reference genome of this species (Golicz et al., 2016a). Therefore, supragenomes were evolved to contain the whole genomic content of a single plant species, comprising both core and dispensable genomic regions of all species individuals (Golicz et al., 2016b). Thus, engaging wild relatives in a supragenome offers a good technique to retrieve genes formerly and unintentionally lost throughout breeding and domestication. These losses may be due to relevant abiotic/biotic stresses. Exploring wild relatives of a plant species to widen the genetic pool of diversity has enabled untapped gene introgression into sober varieties, novel domestication of promising crops, and introgressomics techniques to comply with climate shift (Singh Bakala et al., 2021). Supragenomic research has been conducted on different plant species, e.g., rice, wheat, soybean, and maize (Yuan et al., 2023). It has currently been stretched to a generic level to compose a supersupragenome. Moreover, as these wild relatives normally grow in diverse settings, they may contain genes that are silenced or absent in their corresponding and domesticated varieties. In contrast, employing plant–nematode interactions via RNA interference (RNAi) pathways has proven to enhance benign and reliable pest control, e.g., PPNs. Therefore, Abd-Elgawad (2022b) documented the standpoint that many genes, other than the intended one, in the same plant may react to RNAi knockdown differently, and therefore, other factors such as the resistant phenotypes of nematode strains should be examined as well. This does not exclude the fact that many other genes may be quite useful to comply with climate shift. Consequently, the genomic analysis via supragenome can surely advance breeding via introgression of further genes exclusively found in wild relatives for climate resilience (Zhang & Batley, 2020). Some techniques such as map-to-pan (Hu et al., 2019), iterative mapping (Golicz et al., 2016a), and the de novo assembly (Li et al., 2014) are commonly used to establish a supragenome. Additionally, supragenome graphs could be set to represent variation in thorough formats of genomic graphs to bolster more reliable trait linkage analysis. A relevant graph was applied to estimate millions of variants in 838 genomes of tomato plants which achieved 24% enhancement in the heritability related to linkage analysis (Zhou et al., 2022). Yuan et al. (2023) expected that with the continuous reduction in charges for sophisticated DNA sequencing tools that backs large-scale population investigations, supragenomes and specifically related graphs will be the novel foundation that represents the species-genomic diversity.

10.3.3.3 Investigations for Trait Associations

Yuan et al. (2023) confirmed that unveiling the mechanisms of crop response involving trait associations to various stressors resulting from a changing climate are key factors to understand and consequently boost crop resilience. These factors comprise signaling pathways, gene expressions, regulatory regions, and the correlating linkages. Analysis of trait association is a significant technique that permits to identify genomic loci/chromosomal regions that influence qualitative/quantitative characteristics. Such an analysis can assist in identifying loci that respond to various stresses during breeding crops for climate resilient. Employing such an analysis regarding wheat yield under a hot and dry settings for plant growth, Tura et al. (2020) could identify 27 QTL for thousand-grain weight and 24 QTL for yield on chromosome 1B. There have been more than 1000 GWAS conducted in major crops, comprising rice, wheat, soybean, maize, and barley (Tibbs Cortes et al., 2021). Compared to QTL analysis, the resolution in genome-wide association studies is much higher. Therefore, the latter studies are able to characterize candidate genes for definite attributes as linkage disequilibrium is small (Scheben et al., 2017a). They can provide a strong tool to unveil the genotypes and phenotypes associations and the ease characterization of nominated genes and/or their variation that has key roles in agronomic attributes. A main challenge of trait association researches is the variation in genotypes as impacted by ecological interactions. Frequently, evaluating sober varieties is typically done under favorable settings, but such an evaluation would be less useful in unfavorable environment that may be predicted in future climate change.

10.3.3.4 Genome and Genetic Engineering

Herein, genome editing/engineering refers to shifts in DNA of plants through DNA insertion, modification, deletion, and replacement, but genetic engineering engages introduction of external genetic material. Both techniques can play important roles for climate resilient plant genotypes. So, their related approaches such as genetic modification, mutagenesis, RNA interference (RNAi), and genome engineering could reinforce classical plant breeding via better grasping of gene functions to acquire desired traits into novel bolstered genotypes. Such an editing is currently developing via various approaches: DNA base editing, DNA free genome editing, and prime editing (Singh Bakala et al., 2021). In contrast, mutagenesis can motivate random mutations in plant germplasm via various tools, e.g., X-ray radiation, certain chemicals, and gamma-ray radiation. Merits and demerits of such tools in introducing general mutations with novel genes have recently been reviewed (Abd-Elgawad, 2023a; Yuan et al., 2023).

Genome and genetic editing tools have demonstrated great capacity in boosting crop traits like resistance to plant pests and resilience to the climate shift. For instance, CRISPR/Cas (the clustered regularly interspaced short palindromic repeats/CRISPR-associated protein) systems are utilized for exact modulation of

intended nucleotide in plants (Scheben et al., 2017a). Yuan et al. (2023) referred to CRISPR/Cas9, CRISPR/Cas12, and CRISPR/Cas13 as the most prevalent devices for genome editing in a descending order. Genome editing via CRISPR/Cas tools can manifest predictably shifted phenotypes. Obviously, the acquired traits may be gained in a less time relative to classical breeding schemes. Key crops like tomato, wheat, rice, and soybean (Yuan et al., 2023) could have enhanced yields via applying CRISPR/Cas9. This latter could target and modify yield-relevant genes such as those responsible for panicle and plant architecture as well as grain size/number (Li et al., 2016). In this vein, such an editing of genes in rice has led to elevated yield up to 68% per panicle (Zhou et al., 2022). Application of the same device (CRISPR/Cas9) has resulted in mutations in the rice gene that raised tolerance in the plants for salinity (Zhang et al., 2019). Interestingly, CRISPR/Cas9 has advanced the optimization of crop quality/nutrition through improving transformation protocols for certain plant species; e.g., barrel clover, cowpea, chickpea, miyakogusa, and soybean (Bhowmik et al., 2021). Also, Lou et al. (2017) revealed that OsSAPK2 in rice plants is responsible for increased tolerance to drought conditions. The CRISPR-Cas12a/Cpf1 has recently developed for application in rice. Hence, using another system (CRISPR-Cas12a/Cpf1) for rice plants could knock-out OsEPFL9 gene resulting in minimizing stomata number per leaf with consequent boosting of efficiency in water use especially under stressed environment (Yin et al., 2019). Moreover, the swift evolving of CRISPR-based techniques and tools has been offering options for controlling plant pathogens and pests; e.g. fungi, nematodes, viruses, and bacteria. Their relevant applications against such pathogens/pests via raising resistance of various plant species were recently reviewed (Abd-Elgawad, 2023a). Enhancement of disease resistance was typically attained by modifying related factors of the host plant, e.g., genes responsible for plant susceptibility. Abd-Elgawad (2023a) presented examples of economically important crops where CRISPR/Cas9 system was tried to enhance their resistance for plant-parasitic nematodes. The genome editing by this system could aid in boosting desired characteristics in plants that have a limited genetic pool or meager resistance sources. This strategy was also utilized to introduce resistance to the fungus causing powdery mildew of wheat (Zhang et al., 2017). Similarly, CRISPR/Cas systems were used to edit the DNA genome for upgrading resistance against viruses, e.g., against turnip mosaic virus (Aman et al., 2018). A few issues may rise during the editing which might result in unpredictable phenotypes, but rapid progress is being achieved to detect and reduce off-target cases. Generally, the CRISPR/Cas-related systems can supply promising approaches to expedite and ease the production of elite varieties/cultivars for climate resilient plant genotypes, bolstering global food security.

Two other terms, i.e., cisgenesis and intragenesis, related to genetic delivery bode well for a “clean” DNA transfer system of genes (Caradus, 2023). Cisgenesis refers to a gene transfer from the same/closely related species accompanied by its own regulatory promoter as well as its terminator. Consequently, a shift in the expression model may occur for the intended gene guided by elements controlled via other genes. Likewise, intragenesis engages constructing the whole vector region dedicated for delivery to a species from the genome of the same species.

Thus, transfer via intragenesis (DNA fragment) or cisgenesis (a gene with its regulatory promoter and terminator) between individuals of the same/cross-compatible species varies from transgenesis because both cisgenesis and intragenesis can naturally take place (van Rijssen & Morris, 2018).

10.3.3.5 Cutting Short of Plant Generation Time

As the life cycle of plants has usually long generation times, introducing techniques as seed increase nurseries and winter breeding could significantly decrease release times of several crops as peanut (O'Connor et al., 2013). Yet, these techniques allow only two generations under optimal environmental conditions in a calendar year. Therefore, further speed breeding technique was developed and could minimize time of full-season maturity peanut generation from 145 down to 89 days. This was attained via adjusting constant light and proper temperature, controlled settings, and a single seed descent breeding design under controlled greenhouse conditions (O'Connor et al., 2013). Speed breeding is progressing as a sober device to enhance plant breeding of key crops like wheat, barley, and rice (Singh Bakala et al., 2021). Superior speed breeding can be employed by merging speed breeding into recent technological approaches such as gene editing. Singh Bakala et al. (2021) reported that such a merging can swiftly shift the genes for better adaptation with a variety of unfavorable biotic/abiotic factors related to climate changes. Eventually, integrating all the aforementioned tools with such fast breeding techniques would ease and accelerate availability to targeted alleles and new variation found in wild relatives of the intended plant species. Currently, such tools along with classical plant breeding have already led to develop key varieties, cultivars, and general genotypes of economically important plant species for climate change-resilient strategies (Table 10.1).

10.4 Additional Practices to Optimize Climate-Resilient Plant Phenotypes

Other technological devices for such climate resilience are related to general plant condition which should be optimized by growers/stakeholders. That is because the plant production is affected by both its environment and genetic constitution.

planting, during planting, and/or after harvesting the crop. In this vein, numerous complex but valuable traits such as crop yield could not manifest their ability to properly show all related components responsible for and inherent to these traits because of the reactions between environmental and genetic components of such different phenotypes.

Obviously, relations between genotypes and phenotypes are not strictly linear; small shifts on one hierarchical model may possess greater efficacy on other levels

Table 10.1 Examples of using various crop-breeding techniques for climate resilient plant genotypes

Plant species/ genotype	Target/improved trait	Used technique	References
Raphanobrassica	Merging superior yield, palatability, and quality of kale to the enhanced drought and radish tolerance to insects/diseases	Artificially made interspecific hybrids (cross of <i>Raphanus sativus</i> and <i>Brassica oleracea</i>)	Chakwizira et al. (2021) and Dumbleton et al. (2022)
Rice	Submergence tolerance	Marker assisted breeding	Septiningsih et al. (2009)
Rice	Number of grains, dense erect panicles, and better grain size	CRISPR/Cas9	Li et al. (2016)
Tomato	Resistance to viruses causing tomato spotted wilt and cauliflower mosaic	Intragenesis	Kumar et al. (2020)
Tomato	Enhanced vitamin D3 expression, to grant a based source of D3	CRISPR/Cas9	Li et al. (2022)
Canola	Cibus' herbicide-tolerant SU canola™	Oligo-directed mutagenesis	Gocal (2015)
Wheat	Heat tolerance	Genome-wide association studies	Paliwal et al. (2012)
Barley	Boosted grain phytase performance	Cisgenesis	Holme et al. (2020)
Maize	High amylopectin starch content	RNA-directed DNA methylation (Epigenesis)	Waltz (2016) and Kumar et al. (2020)
Chickpea	Resistance to drought, cold, salinity, and heavy metal stresses	RNA sequencing	Abdelrahman et al. (2018)
Soybean	Salt tolerance	RNA sequencing	Qi et al. (2014)
Cotton	Tolerance to drought and salts	Genome-wide association studies	Yuan et al. (2019)

(Singh Bakala et al., 2021). Hence, crop production practices should also comply with the climate changes for best crop yields. Such practices may comprise upgrading resilience in soil via proper fertilization and tillage, avoid bare soil, use of soil/organic amendments, and wise crop rotation/intercropping. Singh Bakala et al. (2021) referred to such related practices as adapted crop cultivars and agro-ecosystems, rainwater collecting and recycling, upgrading farm machinery, crop contingency plans, and weather-based agricultural advisories. Still, further explorations to boost production exercises are needed to optimize the resilience for climate changes with an end in view to raise crop yields. To name a few, advanced citrus production system to maintain acceptable yield against the spontaneous introduction of alien pathogens in Florida, USA, reduced EPN populations and exacerbated damage caused by subterranean pests (Campos-Herrera et al., 2013). Therefore,

advanced molecular studies via fine-scale taxonomic resolution (Dritsoulas et al., 2021) and other PCR-based approaches (Abd-Elgawad, 2024) are ongoing to precisely identify species and related modes of action by which EPN communities are regulated/functioning and to examine physical settings and conditions that can conserve EPNs (Campos-Herrera et al., 2013). Obviously, timely application of such a safe BCA can not only raise peanut germination rate but also decrease the existing root pests (Shehata et al., 2021). Also, Duncan et al. (2013) found that adjusting sites of citrus trees can conserve EPNs, decrease weevil feeding, and enhance tree development and fruit production. Admittedly, increased knowledge on genotypes-phenotypes interactions merged into marker-assisted selection and transcriptomic analysis are expected to ease and speed acting towards developing climate resilient plant phenotypes. So, it is apparent that other tools and techniques are still in the pipeline to challenge bad consequences of climate shift on crop production. For instance, digital breeding is suggested (Jeon et al., 2023) to evolve predictive breeding techniques and diminish human intervention by automatic procedure of breeding design, generating breeding populations, and considering various settings throughout the breeding plans. Also, Benitez-Alfonso et al. (2023) have recently put down schemes that harness such increased knowledge to boost intensification of durable plant genotypes for promising climate resilience.

10.5 Conclusions

It is apparent that the current challenge of changing climate with its bad consequences on decreasing crop productivities worldwide necessitates prompt solutions to defeat issues of food security. Hence, manipulation of crop genomics for climate-resilient plant phenotypes should be incorporated into classical plant breeding for further optimization of crop productions. Such manipulation can comprise high throughput and/or high resolution of crop genomics-related processes for plant breeding, e.g., speed breeding, DNA sequencing, and phenotyping/genotyping technology. By incorporating the details from genomics into sophisticated phenotyping and modern genome editing, genomics-assisted breeding can furnish a novel foundation to develop stress-tolerant crop genotypes in terms of elite cultivars and varieties. Successful examples of these approaches are not limited to their current usefulness, but they are poised for renewed upgrades as more innovative tools to integrate relevant optimized processes are becoming widely available.

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Chapter 11

Genome Editing for Climate-Adaptive Crops



Prasann Kumar

11.1 Background

Climate change substantially risks worldwide agriculture, impacting food security and livelihoods, especially in susceptible regions. Climate change, characterised by escalating temperatures, modified precipitation patterns, and heightened occurrence of extreme weather phenomena such as droughts, floods, and storms, negatively impacts agricultural productivity. These modifications lead to diminished agricultural output, modified cultivation periods, and heightened susceptibility to pests and diseases, presenting significant hazards to global food production systems. According to the Intergovernmental Panel on Climate Change (IPCC), if significant adaptation strategies are not implemented by 2050, agricultural yields could decrease by as much as 25%. It is imperative to promptly cultivate crops that endure these shifting conditions to guarantee consistent food production and uphold global food security (Goud et al., 2022; Devi et al., 2023c). Given the circumstances, it is evident that there is a pressing need to develop crops that can adapt to climate change. Conventional breeding techniques, although efficient, are labour-intensive and may not be able to adapt quickly to the fast-changing environment. In addition, the genetic variation present in natural populations may not be adequate to provide the required characteristics for withstanding extreme climatic conditions. Hence, novel strategies are required to augment crops' resilience, productivity, and sustainability. Climate-adaptive crops can be genetically modified to express characteristics such as resistance to drought, ability to withstand high temperatures, and enhanced efficiency in nutrient utilisation. These modifications allow the crops to flourish in challenging conditions and sustain high yields. Furthermore, these crops can be genetically modified to withstand the increasing threats posed by pests and

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diseases worsened by climate change. This would decrease the need for chemical interventions and encourage the adoption of more environmentally friendly agricultural methods. The CRISPR-Cas9 system and other genome editing technologies have transformed plant breeding and unlocked unparalleled possibilities for creating climate-resilient crops. CRISPR-Cas9, which stands for Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated protein 9, enables accurate alterations to the DNA of living organisms. The process involves utilising a guide RNA (gRNA) to identify particular genome sequences selectively. Once identified, the Cas9 enzyme induces the formation of double-strand breaks. Subsequently, the cell's inherent repair mechanisms mend these breaks, leading to specific alterations such as mutations, insertions, or deletions. This technology's simplicity, precision, and efficiency have established it as the favoured tool for genome editing in various organisms, including plants. Aside from CRISPR-Cas9, researchers have also utilised other genome editing tools like TALENs (Transcription Activator-Like Effector Nucleases) and ZFNs (Zinc Finger Nucleases) in plant studies. TALENs and ZFNs function similarly to CRISPR-Cas9 by inducing targeted double-strand breaks in DNA. TALENs employ modifiable DNA-binding domains derived from transcription activator-like effectors to selectively identify particular DNA sequences, whereas ZFNs utilise zinc finger proteins to pinpoint specific locations. While these technologies are effective, they are typically more intricate and less adaptable than CRISPR-Cas9, which has quickly emerged as the prevailing technique in the field. Genome editing has demonstrated encouraging outcomes in various key crops when applied in agriculture. For example, scientists have created genetically modified rice plants with improved ability to withstand drought conditions by modifying genes related to root structure and water usage efficiency. Heat-resistant wheat varieties have been developed through genetic modification of genes linked to heat shock proteins, which safeguard plants against temperature stress. Genetic modification has successfully enhanced the efficiency of nutrient utilisation in maize by modifying genes responsible for nitrogen absorption and assimilation. This has resulted in a decreased reliance on artificial fertilisers and a reduction in negative effects on the environment. In addition, the resistance of crops such as tomatoes and potatoes to pests and diseases has been improved by specifically targeting genes associated with plant immune responses and the recognition of pathogens (Kumar et al., 2018c, 2018e, 2021a; Kumari et al., 2022). The potential applications of genome editing technologies have been further expanded due to recent advancements. High-fidelity Cas9 variants and advanced delivery methods, such as nanoparticles and viral vectors, have significantly improved precision and efficiency. The technique of multiplex genome editing has been effectively showcased in crops such as rice and maize, enabling the simultaneous targeting of multiple genes and facilitating the accumulation of multiple advantageous characteristics. Gene drive systems have the potential to effectively control pests and diseases by rapidly spreading resistance traits throughout populations. Nevertheless, these technologies also give rise to apprehensions regarding off-target effects, which refer to unintended genetic alterations that may result in unforeseen repercussions. Scientists are working to reduce these risks by developing more precise gRNAs and enhancing

methods for detecting off-target effects. The implementation of genome editing in agriculture also gives rise to ethical and regulatory concerns. The public's perception and acceptance of genome-edited crops exhibit significant variation, influenced by cultural, social, and political factors. Ensuring open and clear communication regarding the advantages and drawbacks of genome editing, along with the active participation of relevant parties in decision-making procedures, is essential for establishing trust and fostering acceptance. The regulatory frameworks for genome-edited crops vary among regions, with certain countries categorising them similarly to genetically modified organisms (GMOs), while others have less stringent regulations. It is crucial to align these regulations and establish their foundation on scientific evidence to facilitate the worldwide advancement and implementation of climate-adaptive crops. Intellectual property concerns also emerge when considering the patents associated with genome editing technologies and modified crops, which can affect the accessibility and affordability of these resources for farmers, especially in developing nations (Devi et al., 2024d; Dey et al., 2024; Kumar & Choudhury, 2024a; Kumar & Raut, 2024; Saurabh et al., 2024). Adopting a well-balanced strategy that promotes innovation while guaranteeing fair and equal access to technology is necessary to tackle these challenges. Genome editing provides a potent means to create climate-adaptive crops, effectively tackling the pressing requirement to improve agricultural resilience in the face of climate change. CRISPR-Cas9, TALENs, and ZFNs are advanced technologies that enable accurate and effective modifications to crop genomes. These technologies can introduce desirable traits such as drought tolerance, heat resistance, and improved nutrient use efficiency. Recent advancements have further expanded the potential of genome editing. Nevertheless, the journey is still ongoing. Continued research, collaboration, and transparent communication are important and indispensable for fully harnessing the potential of genome editing in developing climate-adaptive crops. Utilising genome editing techniques can be instrumental in ensuring food production, advancing sustainability, and bolstering global food security in the face of ongoing climate change impacts on agriculture (Fig. 11.1).

11.2 Genome Editing Technologies

Genome editing technologies have greatly transformed biological research and agricultural science by allowing accurate modifications to the genetic material of living organisms. CRISPR-Cas9 has emerged as the most prominent technology among these options due to its simplicity, efficiency, and versatility. CRISPR-Cas9, an abbreviation for Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated protein 9, employs a guide RNA (gRNA) to selectively target particular DNA sequences in the genome. After identifying the target sequence, the Cas9 enzyme initiates a double-strand break in the DNA. The cell's inherent repair mechanisms, such as non-homologous end joining (NHEJ) and homology-directed repair (HDR), are responsible for fixing the break. NHEJ typically introduces small

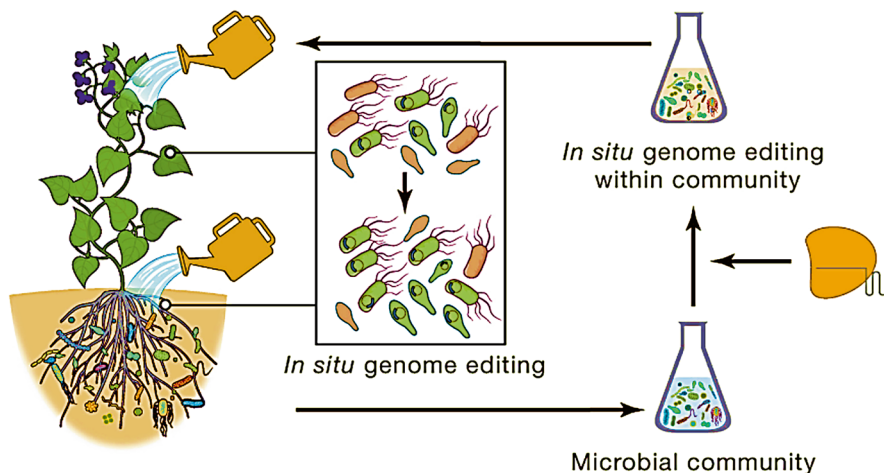


Fig. 11.1 Modifying the plant microbiome to improve crop growth and pathogen resistance

insertions or deletions (indels), while HDR can integrate an external DNA template into the genome. CRISPR-Cas9's accuracy and flexibility have rendered it a potent instrument for generating specific genetic alterations, rectifying hereditary abnormalities, and instilling novel characteristics in diverse organisms, such as plants. The potential of CRISPR-Cas9 is extensive, evoking optimism and assurance in its capabilities (Choudhury et al., 2024; Devi et al., 2024a; Kumar et al., 2024a, 2024d, 2024f; Sharma & Kumar, 2024). Transcription Activator-Like Effector Nucleases (TALENs) are a notable form of genome editing technology. TALENs have two primary constituents: a DNA-binding domain obtained from transcription activator-like effectors (TALEs) and a FokI nuclease domain. Modifying the repeat-variable di-residues (RVDs) within the TALE repeats makes it possible to customise the DNA-binding domain to recognise particular DNA sequences selectively. Upon binding to the target DNA, the FokI nuclease induces a double-strand break, resembling the mechanism of CRISPR-Cas9. Subsequently, the cell's inherent repair mechanisms mend the fracture, facilitating specific alterations in the genome. TALENs possess a high specificity level due to their DNA-binding domains that can be programmed. They have proven effective in various applications, such as gene knockouts, insertions, and corrections. Nevertheless, designing and constructing TALENs are arduous and time-consuming compared to CRISPR-Cas9, restricting their extensive implementation. Zinc Finger Nucleases (ZFNs) are a genome editing tool developed before CRISPR-Cas9 and TALENs. Zinc Finger Nucleases (ZFNs) comprise a zinc finger protein domain that selectively identifies particular DNA sequences and a FokI nuclease domain that creates a double-strand break. Zinc fingers can attach to three DNA building blocks known as nucleotides. Combining multiple zinc fingers makes it possible to develop zinc finger nucleases (ZFNs) that can accurately target longer DNA sequences. Zinc fingers possess a high degree of modularity, enabling the customisation of Zinc Finger Nucleases (ZFNs) to

effectively recognise a diverse array of DNA targets. Although ZFNs are highly versatile, their design and construction are intricate, necessitating proficiency in protein engineering. Furthermore, off-target effects and cytotoxicity have raised concerns regarding applying ZFNs, thereby restricting their usage in specific contexts. However, ZFNs have played a crucial role in the initial attempts at genome editing and have laid the foundation for more sophisticated technologies. The difficulties associated with TALENs and ZFNs highlight genome editing technologies' intricate and profound nature. When evaluating CRISPR-Cas9, TALENs, and ZFNs, various factors should be considered, such as the simplicity of design, effectiveness, precision, and adaptability. CRISPR-Cas9 is notable for its straightforwardness and expedited design process. CRISPR-Cas9 technology can be made widely available to researchers because the gRNA, which directs the Cas9 enzyme to the desired DNA, can be easily synthesised and tailored to specific needs. The efficacy of CRISPR-Cas9 in generating precise genetic alterations is also remarkable, exhibiting high rates of successful modifications observed in diverse organisms. Nevertheless, a significant obstacle linked to CRISPR-Cas9 is the possibility of off-target effects, wherein the Cas9 enzyme induces breaks at unintended sites within the genome. Efforts have been made to reduce the unintended effects of CRISPR-Cas9 technology by improving the accuracy of Cas9 variants and the algorithms used to design gRNA. TALENs provide a high level of specificity because their DNA-binding domains can be customised to recognise specific DNA sequences with minimal unintended effects on other DNA sequences (Devi et al., 2024c, 2024e; Kumar et al., 2024e; Kumar, 2024a; Kumar & Choudhury, 2024b; Pandey et al., 2024). The high specificity of TALENs makes them well suited for applications that require precise targeting. Nevertheless, the arduous and time-consuming process of constructing TALENs can be a disadvantage, especially compared to the swift design process of CRISPR-Cas9. Efficient binding and cleavage in the modular assembly of TALENs necessitate meticulous optimisation, posing a potential obstacle to their widespread adoption. Zinc finger nucleases (ZFNs), although highly adaptable and capable of selectively binding to a diverse array of DNA sequences, are the most intricate to formulate and assemble. Expertise and technical skills are necessary to engineer zinc finger proteins with high specificity. Zinc finger nucleases (ZFNs) also exhibit a greater tendency for off-target effects and cytotoxicity, which can restrict their usefulness in certain situations. Notwithstanding these difficulties, ZFNs have been effectively employed in diverse genome editing applications, specifically in initial attempts to alter plant and animal genomes. Genome editing technologies, including CRISPR-Cas9, TALENs, and ZFNs, have transformed genetic engineering, which presents distinct benefits and difficulties. CRISPR-Cas9 is widely recognised for its straightforwardness, effectiveness, and adaptability, making it the favoured instrument for numerous researchers. TALENs offer exceptional specificity and accuracy, although they necessitate more labour-intensive construction procedures. Although highly adaptable, zinc finger nucleases (ZFNs) present the greatest design and construction intricacies due to potential off-target effects and cytotoxicity issues. The selection of a genome editing tool is contingent upon the application's specific requirements, such as the target organism, the

desired genetic modification, and the acceptable compromises between user-friendliness, specificity, and effectiveness. As genome editing technologies progress, it is anticipated that accuracy, effectiveness, and availability enhancements will increase their usefulness in research and agricultural contexts, ultimately leading to crops with enhanced characteristics and the ability to withstand environmental challenges (Table 11.1 and Fig. 11.2).

11.3 Applications in Major Crops

Genome editing technologies have revealed a significant capacity to improve the durability and efficiency of important crops. This potential shows great promise in advancing drought-resistant crops, which is crucial given the growing water scarcity caused by climate change. An intricate combination of physiological, biochemical, and molecular mechanisms influences the ability of plants to tolerate drought. Primary tactics involve enhancing water absorption and retention, improving roots' structure, and regulating pathways that respond to stress. Researchers have effectively utilised CRISPR-Cas9 to modify genes associated with the abscisic acid (ABA) signalling pathway, which is crucial in regulating plant water stress responses. Researchers have developed rice and mouse strains with enhanced resistance to drought by specifically modifying genes like *OST1* and *PP2C*, which are crucial for regulating stomatal closure and water retention. In addition, manipulating genes such as *DRO1*, which impact the direction and depth of root growth, has resulted in the development of crops with more extensive root systems (Kumar et al., 2018a, 2024b; Kumar & Dwivedi, 2020; Devi et al., 2023b; Dey et al., 2023a; Sharma et al., 2023b; Kumar & Dey, 2024). These roots can reach water sources in deeper soil layers, improving their ability to withstand drought. Furthermore, the ability of crops to withstand high temperatures is a crucial characteristic for sustaining agricultural output in a progressively warmer environment. Heat stress negatively impacts plant growth, development, and yield by interfering with cellular processes such as photosynthesis and protein stability. Plants utilise diverse strategies to deal with heat stress, including producing heat shock proteins (HSPs) that aid in preserving protein functionality and resilience. Genome editing technologies have facilitated the accurate manipulation of genes associated with heat stress responses. For example, the CRISPR-Cas9 system has been employed to augment the expression of heat shock protein (HSP) genes in crops such as wheat and tomato, leading to enhanced resistance to high temperatures. An alternative method entails modifying genes linked to the heat shock transcription factors (HSFs), which control the activation of various heat-responsive genes. Researchers have improved the performance of HSFs to create crops that are more resistant to high temperatures, resulting in consistent yields even in heat stress conditions. Enhancing nutrient use efficiency is a vital objective for sustainable agriculture, as it decreases reliance on synthetic fertilisers and mitigates environmental consequences. Nitrogen, phosphorus, and potassium are indispensable elements for the growth of plants, and their

Table 11.1 Different technology and its advantages and disadvantages

#	Technology	Advantages	Disadvantages
1	CRISPR/Cas9	– High precision – Versatile – Easy design and use – Efficient across organisms	– Potential off-target effects – Complex delivery systems – Ethical and regulatory concerns
2	TALENs (Transcription activator-like effector nucleases)	– High specificity – Effective in various organisms – Established technology	– Complex design – Expensive – Potential off-target effects
3	Zinc Finger Nucleases (ZFNs)	– Targeted editing – Long history of use – Effective in many species	– Difficult to design – High cost – Potential off-target effects
4	Meganucleases	– High specificity – Effective in various organisms – Targets long DNA sequences	– Difficult to engineer – Expensive – Limited flexibility compared to newer methods
5	Base editors	– Precise base changes without double-strand breaks – Reduces unwanted mutations	– Limited to specific types of edits – Still under development
6	Prime editing	– High precision – Wide range of possible edits – Reduces off-target effects	– Complex and expensive – Lower efficiency in some organisms
7	CRISPR/Cas12 (Cpf1)	– Different PAM requirements from Cas9 – Generates sticky ends for easier ligation	– Limited tools and protocols – Potential off-target effects
8	CRISPR/Cas13	– Targets RNA, not DNA – Reduces risk of permanent mutations – Useful for transient edits	– Less developed for genome editing – Potential off-target effects on RNA
9	RNAi (RNA interference)	– Can silence specific genes – Useful for functional genomics – Suitable for transient effects	– Off-target effects – Transient expression – Limited to gene silencing, not editing
11	Homologous recombination	– High precision with genome editing – Useful for gene insertion or correction	– Low efficiency – Complex process – Limited by homologous sequences availability

(continued)

Table 11.1 (continued)

#	Technology	Advantages	Disadvantages
11	Epigenome editing	– Targets epigenetic modifications – Regulates gene expression without altering DNA sequence	– Limited to epigenetic modifications – Less precise compared to other editing technologies
12	CRISPR/Cas9 with donor DNA	– Enables precise insertions – Corrects mutations – Effective across various organisms	– Potential for unwanted insertions – Complex delivery of donor DNA
13	Targeted mutagenesis	– Creates specific mutations – Useful for functional studies – Can be highly precise	– Limited to specific types of mutations – May require additional techniques for practical use
14	Site-directed mutagenesis	– High specificity – Useful for functional studies – Well-established technology	– Labour-intensive – Not suitable for large-scale genomic edits
15	In vivo gene editing	– Direct editing in living organisms – Physiologically relevant – Real-time results	– Complex delivery – Potential off-target effects – Regulatory challenges
16	Ex vivo gene editing	– Editing cells outside the organism – Easier to control and monitor – Suitable for therapeutics	– Requires reintroduction of edited cells – Limited to certain cell types
17	Transposon-based systems	– Introduces large genetic elements – Useful for gene tagging and functional studies	– Potential insertional mutagenesis – Complex to control insertion sites
18	Cre-Lox recombination	– Precise gene editing in specific tissues – Widely used in research	– Requires two-component system – Limited to organisms where Cre-Lox system is functional
19	FLP-FRT recombination	– Similar to Cre-Lox – Useful for reversible modifications – Precise control	– Limited to organisms with FLP-FRT system – Requires two-component system
20	Gene drive systems	– Rapid spread of genetic modifications – Useful for pest control and conservation	– Ethical concerns – Potential ecological disruption – Regulatory and safety issues

(continued)

Table 11.1 (continued)

#	Technology	Advantages	Disadvantages
21	Synthetic biology	– Creates new genetic circuits – Combines multiple genetic elements	– Highly complex – Regulatory and safety concerns – Potential unforeseen consequences
22	Zinc finger activators	– Enhances gene expression with specificity – Useful for functional genomics	– Complex to design – Limited to activation, not editing
23	CRISPR/Cas9 for epigenetic modifications	– Targets epigenetic marks with precision – Regulates gene expression without altering DNA sequence	– Limited to epigenetic modifications – Less established compared to other CRISPR applications
24	Epigenetic reprogramming	– Resets epigenetic states – Useful for regenerative medicine and development studies	– Complex – Limited to specific applications – Requires detailed understanding of epigenetic mechanisms
25	Split Cas9 systems	– Reduces off-target effects – Spatial and temporal control of genome editing	– Complex design – Requires precise control of split components
26	Tethered CRISPR/Cas9	– Targets specific genome locations – Reduces off-target effects	– Complex design – Limited by availability of suitable tethering systems
27	Transcriptional activator-like effectors (TALEs)	– High specificity – Targets specific genes/regions – Useful for functional genomics	– Complex to design and produce – Expensive – Less versatile than CRISPR
28	CRISPR/Cas9 with RNA-guided nucleases	– Tailored to specific sequences – Versatile and efficient	– Potential off-target effects – Requires precise RNA guide design
29	Reprogramming factors	– Induces pluripotency or specific cell types – Useful for regenerative medicine and research	– Complex process – Limited to specific applications and cell types
30	Antisense oligonucleotides	– Inhibits gene expression at RNA level – Useful for gene function studies	– Limited to RNA interference – Potential off-target effects
31	Nano-Cas9 systems	– Delivers CRISPR/Cas9 components using nanotechnology – Improved delivery efficiency	– Development and production challenges – Potential unknown long-term effects

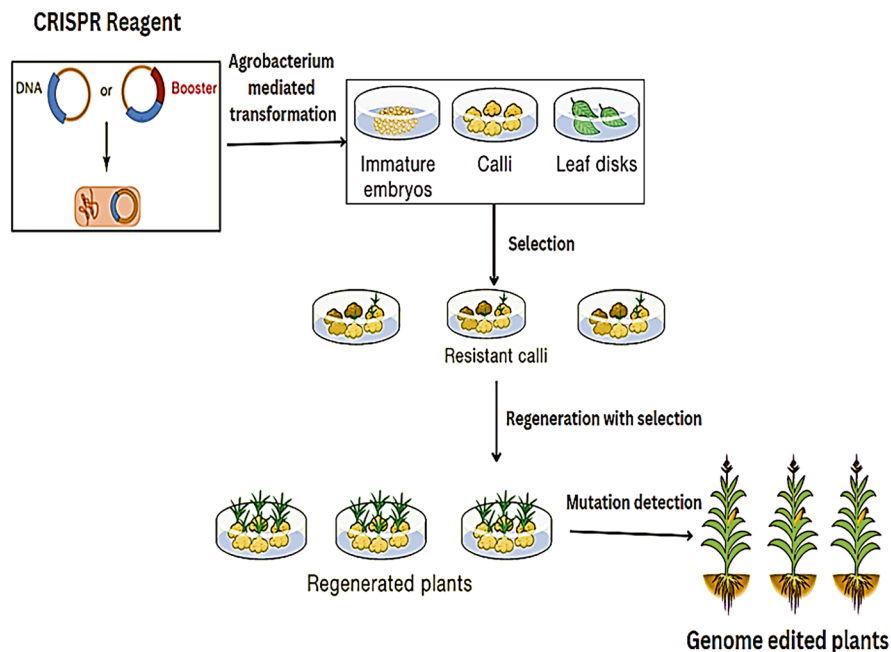


Fig. 11.2 Agnominated transformation

effective absorption and utilisation are crucial for the productivity of crops. The genome editing technique has facilitated the alteration of genes that play a role in nutrient absorption, movement, and incorporation. CRISPR-Cas9 has been employed to modify genes such as *NRT1.1* and *AMT1.1*, which play a role in the absorption and transportation of nitrogen in rice and maize. The alterations have improved the efficiency of nitrogen utilisation, thereby decreasing the reliance on nitrogen fertilisers and encouraging the adoption of more environmentally friendly agricultural methods. Moreover, the enhancement of phosphorus uptake and utilisation in crops like soybean and barley has been achieved by manipulating genes related to phosphorus transporters, such as *PHO1*. By optimising the expression and activity of these transporters, researchers have created crop varieties that can flourish in soils with low nutrient content. This reduces the reliance on chemical fertilisers and improves environmental sustainability. Genome editing technologies have made substantial progress in pest and disease resistance. Pests and pathogens pose a significant threat to crop productivity and food security, thus requiring the creation of crop varieties that are resistant to them. Plants have developed diverse defence mechanisms to counteract pests and diseases, such as synthesising antimicrobial compounds and triggering immune responses. Genome editing has enabled the accurate alteration of genes associated with defence pathways, thereby improving the ability of crops to resist different pests and diseases. CRISPR-Cas9 has been employed to modify genes that produce antimicrobial peptides in crops such as rice

and wheat (Dwivedi & Kumar, 2011; Kumar et al., 2017; Devi & Kumar, 2023a, 2023b; Sharma et al., 2023a). The alterations have resulted in an augmentation of the synthesis of antimicrobial substances, thereby bolstering the ability to combat bacterial and fungal pathogens. In addition, the manipulation of genes responsible for the detection and transmission of pathogen-associated molecular patterns (PAMPs) has enhanced the immune reactions of crops such as tomatoes and potatoes, rendering them more resilient against infections caused by prevalent pathogens like *Phytophthora infestans* and *Xanthomonas* species. Furthermore, genome editing technologies have also improved various significant agronomic traits, including yield, quality, and stress tolerance, in addition to the specific applications mentioned. CRISPR-Cas9 has enhanced rice's grain size and weight by modifying genes such as GS3 and GW2, increasing crop yields. Likewise, the alteration of genes associated with fruit ripening, such as RIN and NOR in tomatoes, has enhanced the overall quality and longevity of the fruit. These advancements exemplify the adaptability and capacity of genome editing in revolutionising crop breeding and agriculture. In addition, advancements in genome editing techniques, such as base editing and prime editing, have broadened the range of tools accessible to scientists. Base editing enables precisely converting one DNA base to another without causing double-strand breaks, thereby minimising the chance of unintended mutations. Prime editing is a more sophisticated method that allows for the exact insertion, deletion, or substitution of DNA sequences, providing enhanced flexibility and precision. These technologies show potential for tackling intricate genetic traits and expediting the advancement of climate-resilient crops. Although genome editing holds great potential, it is crucial to confront the ethical, regulatory, and societal concerns linked to its application. The public's views and acceptance of genetically modified crops edited at the genome level differ depending on the region and are influenced by cultural, social, and political factors. Ensuring open and honest communication regarding the advantages and potential drawbacks of genome editing, along with the active participation of relevant parties in decision-making, is essential for establishing trust and fostering acceptance. Global regulatory frameworks for genome-edited crops vary, with certain countries implementing strict regulations akin to those for genetically modified organisms (GMOs), while others have more lenient approaches. Harmonising these regulations using scientific evidence is crucial to promote developing and implementing climate-adaptive crops worldwide. Moreover, the intellectual property concerns associated with genome editing technologies and modified crops can affect farmers' ability, especially those in developing nations, to access and afford them. Adopting a well-balanced strategy that promotes innovation while guaranteeing fair and equal access to technology is necessary to tackle these challenges (Kumar et al., 2011a; Pankaj et al., 2012a; Pathak et al., 2017; Devi et al., 2023a; Saini et al., 2023; Sinam et al., 2023; Upadhyay et al., 2023). Genome editing technologies have profoundly transformed crop breeding by facilitating the creation of crops that possess heightened resistance to drought, increased tolerance to high temperatures, improved efficiency in utilising nutrients, and enhanced ability to resist pests and diseases. Scientists can create climate-resilient crops using advanced techniques such as CRISPR-Cas9, TALENs,



Fig. 11.3 Applications of major crops

and ZFNs to accurately modify genes that play a role in important stress response pathways. These advancements are essential for guaranteeing food security and sustainability in light of climate change and tackling global challenges. To fully harness the capabilities of genome editing in agriculture, it is crucial to continue conducting research, fostering collaboration, and maintaining transparent communication. These efforts are necessary to address ethical and regulatory concerns and facilitate the widespread adoption of climate-adaptive crops. This collaborative mission necessitates the involvement of all stakeholders, including scientists, policy-makers, and farmers. It is a mission in which we all play a role (Fig. 11.3).

11.4 Recent Advancements in Genome Editing

Recent progress in genome editing has greatly improved the accuracy, effectiveness, and flexibility of these technologies, expanding their range of uses and influence. Significant advancements have been made in enhancing the accuracy and effectiveness of genome editing tools. Conventional CRISPR-Cas9 systems, although groundbreaking, frequently encounter difficulties associated with off-target effects, which involve unintentional editing of genomic regions, potentially resulting in undesirable consequences. In response to this issue, scientists have created more accurate versions of the Cas9 enzyme, such as SpCas9-HF1 and eSpCas9, demonstrating decreased off-target effects. These modified enzymes improve the precision of genome editing by reducing unintended DNA cleavage, thus enhancing the safety and dependability of CRISPR-based applications. Moreover, the progress in guide RNA (gRNA) design algorithms has enhanced the accuracy of target site selection,

thereby decreasing the probability of off-target effects. The advancements have enhanced the accuracy of genome editing, empowering researchers to carry out specific genetic alterations confidently. A notable progress in genome editing is the emergence of multiplex genome editing techniques. Conventional genome editing methods usually focus on modifying one gene or a specific location at a time, which can be restrictive for complex characteristics controlled by multiple genes. Multiplex genome editing enables the simultaneous targeting of multiple genes or genomic regions in a single experiment. This is especially advantageous for polygenic traits, where the collective impact of multiple genes determines the phenotype. CRISPR-Cas9 is highly suitable for multiplex editing because of its modular nature, allowing multiple gRNAs to target different sites within the genome simultaneously. For instance, rice has employed multiplex editing to concurrently deactivate multiple genes related to plant structure, leading to enhanced crop productivity and resilience to environmental pressures. Similarly, in the case of tomatoes, multiplex editing has been used to modify genes responsible for fruit ripening, resulting in improved shelf life and overall quality. This capability greatly expedites the breeding process, enabling the swift advancement of crops with multiple advantageous characteristics. Gene drive systems are a significant breakthrough in genome editing, specifically for controlling pests and diseases. Gene drives are genetic mechanisms that enhance the probability of a specific gene being passed on to offspring, thus facilitating the rapid spread of the gene within a population beyond what traditional Mendelian inheritance would allow (Kumar et al., 2011b, 2013, 2023b, 2024c; Kotia et al., 2021; Kumar & Kumar, 2023; Kumar, 2024b; Kumar & Choudhury, 2024c). CRISPR-based gene drives have been suggested as a method to manage populations of disease vectors, such as malaria-transmitting mosquitoes, by introducing genes that either suppress the population or diminish their capacity to transmit the disease. This technology has great potential in public health and agriculture as it can effectively manage pest populations and mitigate the transmission of vector-borne diseases. It provides a practical solution to these significant global challenges. Nevertheless, utilising gene drives presents substantial ecological and ethical concerns, as the swift dissemination of genetic alterations within natural populations may result in unanticipated repercussions on ecosystems. Therefore, it is imperative to conduct thorough research, evaluate potential risks, and establish regulatory frameworks to guarantee the responsible application of gene drive technology. Although genome editing has great potential, a persistent challenge has been effectively controlling off-target effects. Off-target effects arise when the genome editing tool unintentionally alters regions of the genome that are not the intended target site, resulting in unintended mutations and potentially adverse consequences. Ensuring the safe and effective use of genome editing technologies relies on effectively reducing off-target effects. Multiple strategies have been devised to tackle this problem. As previously mentioned, high-fidelity Cas9 variants are a method for decreasing off-target activity. Another approach entails employing shorter or truncated gRNAs, which have been demonstrated to decrease off-target cleavage by enhancing the specificity of DNA binding. The development of innovative genome editing enzymes, such as Cpf1 (Cas12a), that can identify various DNA

sequences and employ unique cleavage mechanisms offers alternative possibilities that may have reduced off-target effects compared to Cas9. In addition to enzyme-based approaches, computational tools and algorithms are essential in forecasting and reducing off-target effects. Bioinformatics tools can examine the genome and predict possible off-target sites by considering sequence similarity and other relevant criteria. Researchers can diminish the probability of unintended modifications through the meticulous design of gRNAs with minimal anticipated off-target activity. Moreover, GUIDE-seq and CIRCLE-seq enable the thorough examination of off-target effects in genome editing. These methods can identify off-target cleavage events throughout the entire genome, offering valuable information about the precision of genome editing tools and facilitating further improvements. Base editing and prime editing technologies have emerged as notable advancements in genome editing. Base editing enables the accurate conversion of one DNA base to another without causing double-strand breaks, reducing the chances of off-target effects and unintended insertions or deletions. This technology employs modified enzymes, such as cytidine or adenine deaminases, combined with a non-functional Cas9 protein to selectively induce alterations in specific DNA bases. For instance, cytidine base editors (CBEs) can transform cytosine into thymine, whereas adenine base editors (ABEs) can convert adenine into guanine. Base editing has effectively rectified point mutations linked to genetic disorders and introduced favourable crop characteristics, such as herbicide resistance or enhanced nutritional value. Prime editing, a novel advancement, significantly enhances the capabilities of genome editing. Prime editing involves using a Cas9 enzyme that has reduced catalytic activity combined with reverse transcriptase. A prime editing guide RNA (pegRNA) also indicates the desired edit (Kumar et al., 2019; Kumar & Mistri, 2020; Aley et al., 2022; Das et al., 2022; Reddy et al., 2022; Karam et al., 2023; Kumar, 2023; Raj et al., 2024). This system allows for accurate insertions, deletions, and base conversions without double-strand breaks or donor DNA templates. Prime editing provides unparalleled versatility and precision, enabling genetic alterations with minimal unintended impacts. This technology has been exhibited in diverse organisms, encompassing human cells and plants, highlighting its potential for therapeutic and agricultural applications. Recent developments in genome editing have greatly improved these techniques' accuracy, effectiveness, and adaptability. Advancements in accuracy, such as the development of high-fidelity Cas9 variants and improved gRNA design algorithms, have diminished off-target effects, thereby enhancing the safety and dependability of genome editing. Multiplex genome editing facilitates the concurrent manipulation of multiple genes, expediting the advancement of crops with intricate characteristics. Gene drive systems provide novel approaches for managing pests and diseases, but their implementation necessitates thoroughly evaluating ecological and ethical consequences. Implementing techniques such as high-fidelity enzymes, truncated gRNAs, and comprehensive off-target analysis methods is crucial for minimising unintended effects and guaranteeing the safe use of genome editing. Moreover, cutting-edge technologies such as base editing and prime editing offer accurate and adaptable tools for changing genes, thereby broadening the range of possible applications for genome editing.

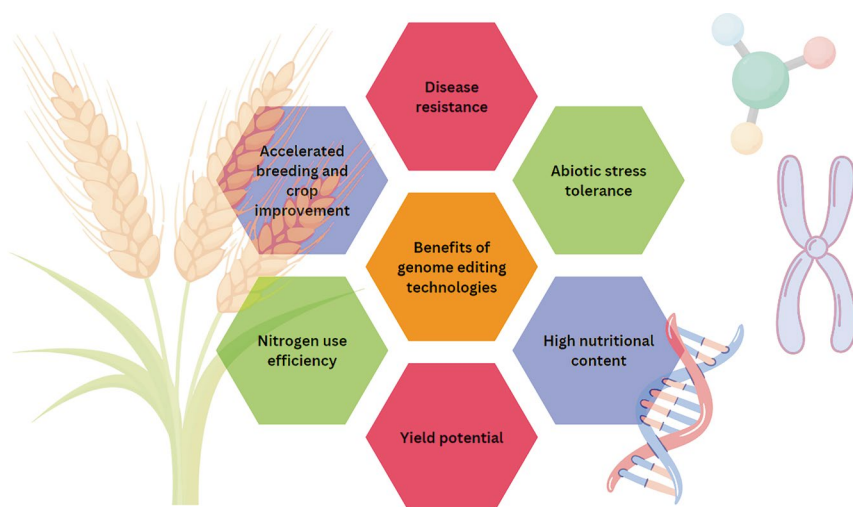


Fig. 11.4 Recent advancements in genome editing

These advancements collectively create opportunities for more effective and environmentally friendly agricultural practices, the creation of crops that can withstand climate change, and potential medical treatments for genetic diseases. This highlights the significant impact that genome editing can have in addressing global challenges (Fig. 11.4).

11.5 Ethical and Regulatory Considerations

The discussion on genome editing in crops revolves around ethical and regulatory factors. These factors include how the public views and accepts something, the rules and regulations set by different regions, concerns related to intellectual property, and the wider ethical consequences. Comprehending and dealing with these factors are essential for the responsible advancement and implementation of genome editing technologies in agriculture. Public perception and acceptance of genome editing in crops differ greatly among regions and communities and are influenced by cultural, social, and political factors. There is significant scepticism and opposition towards genetically modified organisms (GMOs), especially in certain regions like Europe. This scepticism also applies to crops that have been edited using genome editing techniques. This apprehension is fueled by concerns regarding the safety, environmental consequences, and ethical considerations associated with modifying the genetic composition of crops. The public's confidence is additionally hindered by the belief that genome editing is regulated by major agribusinesses whose interests may not coincide with those of consumers or small-scale farmers. Transparent communication regarding the advantages and drawbacks of genome editing is

crucial to establish public trust and acceptance. Interacting with stakeholders, such as farmers, consumers, scientists, and policymakers, can promote a more knowledgeable and equitable comprehension of the technology. Education programs that elucidate the scientific principles underlying genome editing, its potential advantages for ensuring food security and sustainability, and the safety protocols in place can aid in demystifying the technology and addressing public apprehensions (Kumar et al., 2020, 2022c, 2023a; Naik & Kumar, 2020; Dey et al., 2023c; Hidangmayum et al., 2023; Sharma et al., 2023c, 2023d; Kumar & Singh, 2024; Srivastav et al., 2024). The regulatory frameworks for genome editing in crops vary significantly across different regions, indicating differences in acceptance levels and approaches to prevention. Genome-edited crops in the United States are typically subject to less strict regulation than genetically modified organisms (GMOs) as long as the edits do not involve the insertion of foreign DNA. The United States Department of Agriculture (USDA) has stated that it will not impose regulations on plants created using genome editing techniques as long as the modifications could have been accomplished through conventional breeding methods. This regulatory stance aims to promote innovation and streamline the implementation of genome editing in agriculture. Conversely, the European Union (EU) adopts a more cautious approach. In 2018, the European Court of Justice decreed that genome-edited organisms must adhere to the identical stringent regulatory framework as genetically modified organisms (GMOs). This entails undergoing thorough safety evaluations and necessitates proper labelling. Some scientists and industry groups have criticised this decision, arguing that it hampers innovation and puts European agriculture at a competitive disadvantage. China and Brazil, among other regions, have implemented regulatory approaches that balance recognising the potential advantages of genome editing and ensuring safety and environmental protection. Global harmonisation of regulatory frameworks can potentially enhance international trade and collaboration. However, achieving this equilibrium necessitates meticulously evaluating scientific evidence, public apprehensions, and ethical principles. Intellectual property concerns are a significant component of the ethical and regulatory framework surrounding crop genome editing. The possession and command of genome editing technologies and the subsequent crop varieties give rise to fundamental inquiries regarding accessibility, affordability, and fairness. Patents on fundamental genome editing tools, such as CRISPR-Cas9, and the crops created using these technologies have the potential to establish monopolies, which may limit access for small-scale farmers and public research institutions. Consolidating intellectual property among a small number of major corporations could worsen the existing disparities in the agricultural industry, constraining the capacity of smaller entities to reap the benefits of these advancements. In response to these concerns, there have been suggestions to implement open-access models or establish patent pools, enabling wider availability of genome editing technologies. The International Licensing Platform for Plant Breeding and similar collaborative initiatives strive to streamline access to patented technologies while guaranteeing equitable remuneration for innovators (Kumar et al., 2018b, 2018d, 2021c; Kumar & Dwivedi, 2018; Kumar & Pathak, 2019; Kumar & Naik, 2020; Kumari et al., 2023; Sharma & Kumar, 2023; Jagadesh

et al., 2024; Kumar & Choudhury, 2024d). Maintaining a balance in intellectual property systems that encourage innovation while considering the wider societal advantages is essential. This is crucial for promoting fair and equal access to genome editing in agriculture. The ethical ramifications of genome editing in crops go beyond regulatory and intellectual property concerns, encompassing fundamental inquiries regarding the connection between humans and nature, the long-term viability of agricultural methods, and the equitable allocation of risks and rewards. An ethical consideration arises from the possibility of unforeseen ecological and social repercussions from introducing genetically modified crops into the environment. Although genome editing enables accurate genetic alterations, the potential long-term effects on ecosystems and biodiversity remain incompletely comprehended. Edited crops pose a potential hazard of becoming invasive, overpowering native species, or diminishing genetic diversity. The ethical development of genome-edited crops necessitates thorough risk assessments and adopting measures to oversee and alleviate potential ecological consequences. Another ethical concern pertains to the objectives and preferences of genome editing in agriculture. Critics contend that prioritising technological solutions, such as creating crops that can withstand drought or resist pests, might fail to address the fundamental socio-economic and structural factors contributing to agricultural difficulties. Addressing water scarcity solely through technological solutions may divert attention from the necessity of implementing broader water management reforms or policies that promote sustainable farming practices. Ethical considerations encompass the potential ramifications for small-scale and subsistence farmers, who may encounter difficulties accessing and reaping the benefits of genome-edited crops. It is crucial for ethical management to ensure that the development and implementation of these technologies are inclusive and take into account the needs and viewpoints of marginalised and vulnerable communities. Moreover, the ethical discussion revolves around genetic stewardship, which entails the conscientious administration and application of genetic technologies to uphold the inherent worth of living organisms and the wider environmental framework. This viewpoint underscores the importance of modesty and prudence when modifying the genetic composition of plants, acknowledging that human interventions can result in extensive and unforeseeable ramifications. Ethical stewardship necessitates dedication to openness, responsibility, and the principle of taking precautions, guaranteeing that the advantages of genome editing are achieved without jeopardising ecological soundness or social fairness. The responsible development and application of genome editing in crops necessitate the inclusion of ethical and regulatory considerations. The public perception and acceptance of genome editing exhibit significant variation, shaped by cultural, social, and political factors. Open and honest communication involving all relevant parties is crucial for establishing trust and ensuring everyone has a clear and well-informed understanding (Pankaj et al., 2012b; Chakraborty et al., 2021; Kumar et al., 2021b, 2022a, 2022b; Dey et al., 2023b; Devi et al., 2024b; Kumar, 2024c; Kumar & Choudhury, 2024e). Regulatory frameworks vary between regions, indicating different degrees of caution and approval. Aligning these frameworks according to empirical evidence and moral principles can promote global cooperation and

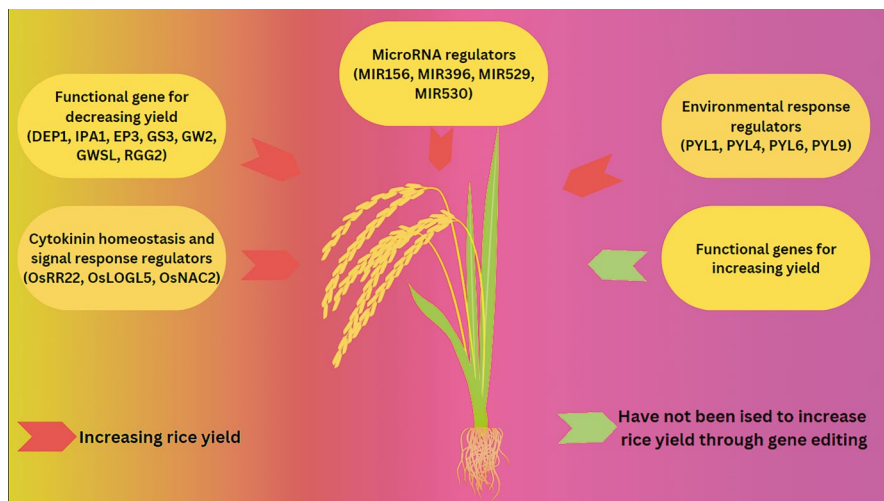


Fig. 11.5 Ethical and regulatory considerations

commerce. Intellectual property concerns provoke significant inquiries regarding accessibility, affordability, and fairness, necessitating well-rounded strategies that foster creativity while guaranteeing wider societal advantages. The ethical implications of genome editing involve potential environmental risks, fairness in society, and the principles of responsible management of genetic resources. These implications emphasise the importance of adopting responsible and inclusive methods to utilise genome editing for sustainable and fair agricultural progress effectively. To fully harness the potential of genome editing while ensuring public trust, environmental integrity, and social equity, it is essential to address these considerations thoughtfully and proactively (Fig. 11.5).

11.6 Implementing Genome Editing in Specific Crops

Implementing genome editing in specific crops has ushered in a new era of agricultural innovation, offering unprecedented opportunities to enhance crop resilience, productivity, and nutritional value. This transformative approach leverages tools such as CRISPR-Cas9 to make precise, targeted modifications to the plant genome, enabling the development of crops that can better withstand environmental stresses, pests, and diseases. Implementing genome editing in specific crops involves several critical stages, from initial laboratory research to field trials and eventual commercialisation. Each stage presents unique challenges and opportunities, ultimately shaping the impact of these advancements on local farming communities. The initial phase of implementing genome editing in specific crops begins with identifying the target traits and the corresponding genes that need to be edited. This requires a

deep understanding of plant genetics, physiology, and the crops' specific challenges. For example, researchers might focus on editing genes associated with drought tolerance in maize, pest resistance in cotton, or nutrient use efficiency in rice. Once the target genes are identified, scientists design guide RNAs (gRNAs) that direct the CRISPR-Cas9 system to editing specific DNA sequences. These gRNAs are introduced into plant cells through *Agrobacterium*-mediated transformation or particle bombardment. After successful genome editing, the modified cells are regenerated into whole plants through tissue culture techniques. Following successful laboratory experiments, the next crucial step is conducting field trials. Field trials are essential for evaluating the performance of genome-edited crops under real-world conditions, providing critical data on their growth, yield, and resilience. These trials help researchers assess whether the edited traits confer the expected benefits and if there are any unintended consequences. For instance, drought-tolerant maize developed through genome editing would be tested in various regions with different climate conditions to ensure its efficacy across diverse environments. Field trials also allow monitoring of the ecological impact of genome-edited crops, such as their interactions with local flora and fauna. This step ensures that introducing these crops does not disrupt local ecosystems or lead to adverse environmental outcomes (Kumar & Dwivedi, 2018; Kumar et al., 2019, 2022c, 2023b; Kumar & Mistri, 2020; Aley et al., 2022; Reddy et al., 2022; Dey et al., 2023c; Kumar, 2023; Kumari et al., 2023; Sharma et al., 2023c; Kumar & Choudhury, 2024c). The commercialisation of genome-edited crops involves navigating a complex regulatory landscape. Regulatory frameworks vary significantly across regions, influencing the pace and extent to which genome-edited crops can be brought to market. In the United States, for example, the regulatory approach tends to be more permissive, with the USDA generally not requiring genome-edited crops to undergo the same rigorous approval process as traditional GMOs, provided no foreign DNA is introduced. In contrast, the European Union adopts a more prudent stance, subjecting genome-edited crops to the same stringent regulations as GMOs. This regulatory variability can impact the global availability and adoption of genome-edited crops, influencing where and how these innovations can be implemented. Successfully navigating these regulatory hurdles is essential for the commercial viability of genome-edited crops, requiring collaboration between scientists, regulatory bodies, and industry stakeholders. Once genome-edited crops reach commercialisation, their impact on local farming communities becomes a critical consideration. Introducing these crops can bring numerous benefits, including increased yields, reduced input costs, and enhanced resilience to environmental stresses. For example, genome-edited rice varieties with improved nutrient use efficiency can reduce the need for chemical fertilisers, lowering farmers' costs and mitigating environmental pollution. Similarly, pest-resistant cotton can decrease the reliance on chemical pesticides, reducing health risks for farmers and the surrounding communities. These benefits can significantly improve the livelihoods of local farmers, especially in regions where challenging environmental conditions hamper agricultural productivity. However, the impact of genome-edited crops on local farming communities is not uniformly positive and depends on various factors, including access to technology, economic

considerations, and socio-cultural dynamics. One of the key challenges is ensuring equitable access to genome-edited crops. Small-scale and subsistence farmers, particularly in developing regions, may face barriers to accessing these innovations due to high costs, lack of infrastructure, or limited knowledge and training. Addressing these barriers requires concerted efforts from governments, non-governmental organisations, and the private sector to provide financial support, infrastructure development, and capacity-building programs. Ensuring that genome-edited crops are affordable and accessible to all farmers, regardless of their economic status, is crucial for maximising their positive impact. Intellectual property rights (IPR) also play a significant role in shaping the impact of genome-edited crops on local farming communities. Patents on genome editing technologies and the resulting crop varieties can create monopolies, potentially restricting access for small-scale farmers and public research institutions. To mitigate this, some have advocated for open-access models or patent pools that allow broader access to these technologies while ensuring fair compensation for innovators. For instance, initiatives like the Open-Source Seed Initiative (OSSI) promote sharing plant breeding innovations to ensure that new crop varieties remain accessible. Balancing the need to incentivise innovation to promote equitable access is essential for the sustainable implementation of genome-edited crops. Cultural and social factors also influence the acceptance and impact of genome-edited crops in local farming communities. Some regions may resist adopting genetically modified crops due to cultural beliefs, traditional farming practices, or mistrust of new technologies. Engaging with local communities, understanding their concerns, and involving them in decision-making processes are vital for fostering acceptance and ensuring that the introduction of genome-edited crops aligns with local values and practices (Dwivedi & Kumar, 2011; Kumar et al., 2011a; Kumar & Dwivedi, 2020; Devi & Kumar, 2023a, 2023b; Dey et al., 2023a; Sharma et al., 2023a; Kumar & Dey, 2024). Participatory approaches involving farmers in developing and testing genome-edited crops can help build trust and ensure that these innovations meet the specific needs and preferences of the communities they are intended to benefit. Additionally, the long-term sustainability of genome-edited crops depends on continuous monitoring and evaluation. This includes assessing their performance under changing environmental conditions, potential impacts on biodiversity, and any socio-economic consequences for local communities. Establishing robust monitoring systems and feedback mechanisms can help identify and address any emerging issues, ensuring that the benefits of genome editing are sustained over time. Collaboration between researchers, policy-makers, farmers, and other stakeholders is essential for creating adaptive and resilient agricultural systems that respond to new challenges and opportunities. Implementing genome editing in specific crops involves a multi-faceted process that includes laboratory research, field trials, regulatory navigation, and commercialisation. Each stage presents unique challenges and opportunities, ultimately influencing the impact of these innovations on local farming communities. While genome-edited crops hold tremendous potential to enhance agricultural productivity, resilience, and sustainability, ensuring their equitable access, acceptance, and long-term sustainability require a holistic and inclusive approach. By addressing the

technical, regulatory, economic, and socio-cultural dimensions of genome editing, we can harness the full potential of these technologies to create a more resilient and sustainable agricultural future.

11.7 Challenges and Future Directions

Although genome editing in crops shows great promise, several obstacles must be overcome to reap its advantages fully. The challenges encompass various technical obstacles, incorporating conventional breeding methods, ensuring long-term viability and ecological implications, and the necessity for further research to advance the field. It is crucial to tackle these challenges to make progress and ensure the responsible application of genome editing technologies in agriculture. A primary technical obstacle in genome editing is attaining exceptional accuracy and effectiveness in altering targeted genes. Although CRISPR-Cas9, TALENs, and ZFNs have made significant progress, the off-target effects issue remains a concern. Unintended modifications can result in unforeseen phenotypes or harmful consequences, undermining the edited crops' safety and dependability. To improve the precision of genome editing tools, researchers are creating more accurate versions of editing enzymes and enhancing the algorithms used to design guide RNA (gRNA) to reduce unintended effects on non-target areas. Ensuring consistent and reliable gene expression in genetically modified crops under varying environmental conditions is difficult. Gene editing efficiency can differ between plant species and even between varieties of the same species, requiring additional optimisation and improvement of techniques for various agricultural purposes. Another technical obstacle involves the transportation of genome editing components into plant cells. Commonly employed techniques, such as *Agrobacterium*-mediated transformation and particle bombardment, have certain limitations, including inconsistent efficiencies and the possibility of inducing unintended genetic alterations. Enhancing the effectiveness and dependability of delivery systems is essential for the wider implementation of genome editing in crops. Researchers are currently investigating novel techniques such as nanotechnology-based delivery systems, electroporation, and viral vectors to improve the accuracy and effectiveness of genome editing. An important factor to consider is the integration of genome editing with conventional breeding techniques. Although genome editing provides the benefit of accurate genetic modifications, traditional breeding methods have been the foundation of crop enhancement for centuries, playing a crucial role in developing diverse and resilient crop varieties. Integrating genome editing with traditional breeding can capitalise on the advantages of both methodologies. Genome editing can introduce advantageous traits into high-quality breeding lines, which can be further improved through conventional breeding to include additional desirable characteristics. This integration can potentially expedite the advancement of novel crop varieties with improved yield, resilience, and nutritional quality. However, attaining this integration necessitates a profound comprehension of the genetic foundation of traits and the

breeding methods specific to each crop species. The responsible deployment of genome-edited crops requires careful consideration of their long-term sustainability and ecological impact (Kumar et al., 2013, 2024c; Kumar & Mistri, 2020; Aley et al., 2022; Kumar & Kumar, 2023; Saini et al., 2023; Upadhyay et al., 2023; Kumar, 2024b; Kumar & Choudhury, 2024c). Although genome editing enables accurate alterations, the potential long-term ecological impacts of introducing these crops into the environment remain incompletely comprehended. Genome-edited crops pose a potential hazard of causing unintended consequences in local ecosystems, such as modifying the relationships between plants and other organisms or leading to a decline in biodiversity. Before the widespread implementation of genome-edited crops, it is imperative to conduct thorough environmental impact assessments to guarantee their long-term sustainability. These assessments should investigate the potential impacts on non-target organisms, the transfer of genes to wild relatives, and the overall ecological equilibrium. Furthermore, it is crucial to consistently monitor genetically modified crops in their natural environment to identify and address any unexpected ecological consequences. Another facet of long-term sustainability is the socio-economic influence on farming communities. Although genome-edited crops can provide substantial advantages, such as higher yields and lower expenses, their implementation must be accompanied by initiatives to guarantee fair access and assistance for small-scale and subsistence farmers. Financial assistance, training, and infrastructure development policies and initiatives are essential to ensure universal access to the benefits of genome editing for all farmers, irrespective of their economic status. It is crucial to tackle these socio-economic aspects to promote inclusive and sustainable agricultural development. When considering the future, multiple opportunities and research requirements arise for progressing genome editing in crops. A promising research avenue involves advancing base editing and prime editing technologies, which enable accurate nucleotide alterations without double-strand breaks. These technologies have the potential to enable more precise and predictable genetic modifications, thereby minimising the risk of unintended effects. Additional research is required to enhance and broaden the scope of these techniques for different crops and traits. Another crucial area of research involves comprehending the intricate genetic networks and pathways that regulate essential agronomic traits. Several genes and their interactions govern numerous advantageous characteristics, such as drought resistance, disease resistance, and crop yield. Progress in genomics, transcriptomics, and proteomics offers a fresh understanding of these intricate networks, facilitating the development of more precise and efficient genome editing techniques. Combining omics approaches with genome editing makes it possible to expedite the creation of crops that possess improved traits and perform better in various environmental conditions. Future research also prioritises the development of genome editing tools that are more efficient and scalable. This encompasses enhancing the methods of delivering genome editing components, refining the efficiency and accuracy of editing enzymes, and creating novel tools for editing multiple genomes simultaneously. Multiplex genome editing enables the concurrent alteration of multiple genes, resulting in the development of crops with intricate characteristics within a single

generation. This capability can greatly expedite breeding and decrease the time needed to create new crop varieties. Ensuring the responsible use of genome editing requires focusing on technical progress and addressing the ethical, regulatory, and social aspects associated with it. It is crucial to establish strong regulatory frameworks that guarantee the safety and environmental sustainability of genome-edited crops while also encouraging innovation. Engaging the public and communicating openly about the advantages and potential drawbacks of genome editing can foster trust and gain acceptance from a wide range of individuals involved. Developing and deploying genome editing technologies must incorporate ethical considerations, including the potential effects on biodiversity, socio-economic inequalities, and the principles of genetic stewardship. Although genome editing has the potential to impact agriculture greatly, several obstacles must be overcome to harness its benefits fully. Ongoing research and innovation are necessary to address the technical challenges of precision, efficiency, and delivery of genome editing components. Integrating genome editing with traditional breeding techniques can harness the advantages of both methods to expedite crop enhancement. Conducting thorough environmental assessments and maintaining continuous monitoring are essential to guarantee genome-edited crops' long-term sustainability and ecological impact. Future research should prioritise advancing genome editing technologies, comprehending intricate genetic networks, and resolving ethical, regulatory, and social concerns. Genome editing has the potential to enhance the resilience, sustainability, and fairness of agriculture by tackling these challenges and pursuing future goals.

11.8 Conclusion

The emergence of genome editing technology signifies a revolutionary period in agriculture, providing potent instruments to tackle the urgent challenges climate change presents. This conclusion provides a concise summary of the main points discussed and emphasises the potential of genome editing in addressing agricultural challenges related to climate change. It also emphasises the need for ongoing research and collaboration to exploit its advantages fully. The main takeaways from our discussion emphasise the significant influence of genome editing technologies, such as CRISPR-Cas9, TALENs, and ZFNs, on enhancing crop quality. These technologies facilitate accurate alterations in crop genomes, resulting in the development of characteristics that improve drought tolerance, heat resistance, nutrient utilisation efficiency, and resistance to pests and diseases. The practical feasibility of these innovations is demonstrated through field trials and commercialisation efforts, highlighting their potential to enhance agricultural productivity and resilience. The ethical and regulatory factors, such as public opinion, legal frameworks, intellectual property concerns, and the wider ethical consequences, play a crucial role in ensuring the responsible implementation and public approval of genetically modified crops. Furthermore, it is crucial to effectively handle the socio-economic consequences on nearby agricultural communities to guarantee fair and sustainable

access to benefits. Genome editing can effectively tackle the challenges posed by climate change in agriculture. Genome editing has the potential to greatly reduce the negative effects of climate change on crop yields and food security. This is achieved by allowing the creation of crops that are more resistant to extreme weather conditions. For example, genetically modified drought-tolerant maize or heat-resistant rice can flourish in areas that frequently experience water scarcity and high temperatures, guaranteeing consistent food production in the face of changing climatic conditions. Moreover, genome editing can potentially improve the efficiency of nutrient utilisation in crops, thereby decreasing reliance on chemical fertilisers and mitigating environmental pollution. Utilising pest and disease-resistant crops can reduce the dependence on chemical pesticides, thereby encouraging the adoption of sustainable agricultural methods and protecting the well-being of farmers. These technological advancements collectively contribute to a farming system that is more robust and environmentally friendly, capable of adjusting to the challenges presented by climate change. However, fully harnessing the complete capabilities of genome editing in agriculture necessitates a focused endeavour in research and collaboration. Ongoing research is crucial to tackle the technical obstacles related to accuracy, effectiveness, and administration of genome editing components. Further refinement and exploration are required for innovations such as base editing and prime editing, which provide greater precision and predictability in modifications. Comprehending the intricate genetic networks that control significant agronomic traits using advanced genomics, transcriptomics, and proteomics is essential for devising efficient genome editing strategies. Moreover, the ethical, regulatory, and socio-economic aspects of genome editing require continuous discussion and collaboration among scientists, policymakers, industry stakeholders, and local communities. It is crucial to urge the scientific community, policymakers, and industry stakeholders to take action to progress genome editing in agriculture. Researchers must persist in developing and improving genome editing technologies, guaranteeing accessibility, efficiency, and safety. Policymakers should strive to achieve global harmonisation of regulatory frameworks, ensuring a delicate equilibrium between the imperative for innovation and safety and environmental concerns. Industry stakeholders can have a significant impact by allocating resources to research and development, facilitating the development of infrastructure and capacity-building programs, and advocating for fair and equal access to genome-edited crops. Establishing trust and gaining acceptance are crucial to actively involving and communicating openly with local communities while addressing their concerns. Genome editing provides a revolutionary solution to the difficulties presented by climate change in agriculture. The potential of this technology to improve the ability of crops to withstand stress, increase productivity, and promote sustainability is vast, offering a more reliable and environmentally friendly food supply in the future. However, harnessing this potential necessitates ongoing investigation, ingenuity, and cooperation across various aspects, such as technological progress, ethical deliberations, regulatory structures, and socio-economic consequences. Through collaboration, the international community can utilise genome editing to establish a

robust, environmentally friendly, and fair agricultural system that can withstand the shifting climate's difficulties and guarantee food security for future generations.

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Chapter 12

Harnessing Biotechnology for Climate-Resilient for Crop Innovations



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12.1 Background

The ever-changing climate leads to a range of adverse effects on agriculture, including increased frequency and severity of droughts, extreme temperatures, and changing precipitation patterns. These changes can reduce crop yields, degrade soil quality, and exacerbate pest and disease problems. Traditional breeding methods, while valuable, are often too slow to keep pace with the rapid environmental changes. (Das et al., 2023) Traditional plant breeding relies on selecting and cross-breeding plants that contain desirable traits over multiple generations. This process is time-consuming and less precise, making it difficult to achieve the specific traits needed for climate resilience, such as drought tolerance, heat resistance, and pest resistance. Biotechnology offers tools like genetic engineering, “CRISPR-Cas9 gene editing, and marker-assisted selection,” which allow for precise modifications at the genetic level. These technologies can significantly speed up the development of crops with desired traits. For example, genetic engineering can introduce drought-resistance genes from other species into staple crops, enabling them to survive in arid conditions (Zenda et al., 2021).

A significant benefit of biotechnology is its ability to enhance genetic diversity within crop species. By broadening the genetic base, biotechnology can help create crops that are extremely resilient to a range of climatic stresses. This diversity is essential for maintaining ecosystems in good shape and verifying long-term food security (Garland & Curry, 2022). Advances in genomics, proteomics, transcriptomics, and metabolomics (collectively known as omics technologies) allow for a

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complete understanding of plant responses to environmental stresses. Integrating these insights with biotechnological tools can lead to the creation of crops that are not only climate-resilient but also nutritionally superior (Cabusora, 2024). Biotechnologically enhanced crops can lead to increased yields and stability, which are vital for farmers’ livelihoods and national economies. By reducing the need for chemical inputs like pesticides and fertilizers, these crops can also promote more sustainable agricultural practices.

12.2 Challenges and Solutions

Developing a climate-resilient crop can be a quite challenging task. Since climate refers to the total of the weather conditions over a large area, for a long period, it can be a daunting task to produce such crops that can yield or sustain the apparent qualities necessary for the plant to survive in a particular climate (Fig. 12.1). A few challenges faced in this regard can be technical, regulatory, social, and economic.

The complexity of climate resilience traits involves several aspects such as drought tolerance, heat resistance, and pest resistance. Identifying all these traits and manipulating them can be tedious and time-consuming which adds up to the challenges already faced. Effective crop improvement often necessitates the integration of multiple technologies, such as proteomics, genomics, transcriptomics, and metabolomics. This integration is intricate and demands advanced bioinformatics tools and computational models to analyze and interpret the extensive data involved. To curb such challenges, we can employ CRISPR/Cas9 and other precise gene-editing technologies to target specific genes associated with climate resilience. These tools can minimize off-target effects and enhance the efficiency of developing desired traits. By applying multi-omics approaches (genomics, transcriptomics, proteomics, metabolomics), we can comprehend complex trait interactions and devise integrated strategies for crop improvement.

Ethical and public concerns also need to be addressed while producing such technologically advanced plants. There is considerable public skepticism and

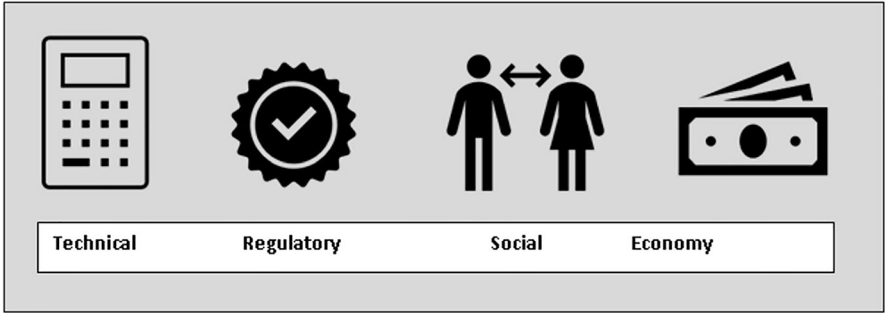


Fig. 12.1 Some of the challenges faced in producing a climate-resilient crop

opposition to GMOs and other biotechnological interventions in agriculture. Misinformation and a lack of understanding about biotechnology can result in resistance from consumers, policymakers, and advocacy groups. Ethical issues surrounding genetic modification, such as potential impacts on biodiversity and natural ecosystems, need to be carefully considered. Balancing the benefits of biotechnology with ethical considerations is essential for gaining public trust and support. Developing climate-resilient crops through biotechnology is an expensive process that demands substantial investment in research and development (R&D). Small and resource-poor farmers may struggle to afford these advanced technologies without financial support and incentives. Although it might seem far-fetched at the moment, it is not impossible.

12.3 Modification of Genes

Modification of genes, also known as genetic engineering, is the process of alternating an organism's genetic material to obtain specific traits. This manipulation is generally achieved by the process of insertion, deletion, or modification of genes within the organism's genome (Snow et al., 2005). Genetic engineering encompasses a range of technologies designed to alter the genetic arrangement of cells, which includes the transformation of genes both within and between species to develop enhanced organisms. By using recombinant DNA techniques, new DNA can also be obtained by isolating and replicating the desired genetic material. Typically, a template is designed to introduce the DNA into the host organism (Aaziz & Tepfer, 1999). This process can also be utilized to remove or “knock out” specific genes, in addition to inserting new ones. The DNA can be inserted randomly within the genome or targeted to a particular location. An organism created using genetic engineering techniques is known as genetically modified (GM), and the resulting organism is known as a genetically modified organism (GMO) (Bleotu et al., 2018). Genetic engineering provides a groundbreaking alternative by enabling the introduction of targeted genes from any given source—be it a microbe, plant, animal, or synthetic—into the recipient or host cells, where they can be directly integrated into the organism's genetic composition. For example, genes that confer resistance to diseases can be inserted into a transgene and directly integrated into the genome of a high-yield crop variety, circumventing the limitations of traditional breeding methods (Hewett et al., 2016). As techniques for creating transgenic organisms continue to progress, today's genetically engineered organisms (GEOs) may eventually be regarded as rudimentary. Moreover, new molecular technologies are anticipated to blur the distinction between what is considered transgenic and what is not. For instance, using transgenic approaches to silence native genes falls into this gray area. Genetic engineering has wide-ranging applications in research, medicine, industrial biotechnology, and agriculture (Beachy, 1999). In research, genetically modified organisms (GMOs) are used to investigate gene function and expression through various techniques, such as loss of function, gain of function,

tracking, and expression studies. Gene knockout strategies can be used to create animal models for the study of human diseases. Beyond the production of hormones, vaccines, and other pharmaceuticals, genetic engineering holds promise for gene therapy to treat genetic disorders (Lindbo & Falk, 2017). Additionally, the techniques used in drug production have industrial applications, including the development of enzymes for laundry detergents, cheese production, and other uses.

The commercialization of genetically modified (GM) crops has provided economic advantages to farmers in several countries but has also sparked significant controversy. This debate began in the early stages of the technology, with anti-GM activists destroying initial field trials. While the scientific consensus is that currently available GM foods pose no greater risk to human health than traditional foods, critics persist in raising concerns about their safety. Other issues include gene transfer, impacts on non-target species, control of the food supply, and intellectual property rights (Abdallah et al., 2015). Genetic engineering holds tremendous potential to address severe genetic disorders or diseases in humans by swapping defective genes with functional ones. It is a crucial research tool for studying the roles of specific genes. Engineered organisms have been used to produce drugs, vaccines, and other products. Additionally, genetically modified crops have been under process to enhance food security by boosting yield, and improving nutritional value, thereby increasing resistance to environmental stresses.

Genetic engineering has a vast array of applications across medicine, research, industry, and agriculture, and it can be applied to a variety of plants, animals, and microorganisms. Bacteria, the first organisms to be genetically modified, can have plasmid DNA introduced to carry new genes that enable them to produce medicines or enzymes used in food processing and other substances (Nuffield Council On Bioethics, 2019). Plants have been genetically modified to protect against insects, resistance to herbicides and viruses, enhanced nutritional value, tolerance to environmental stressors, and even the ability to produce edible vaccines. Most of the GMOs available commercially are crop plants engineered to be either insect-resistant or herbicide-tolerant.

Genetically modified animals are used in research as model organisms and to produce agricultural or pharmaceutical products. These animals might have genes that are knocked out, increased vulnerability to diseases, hormones that promote additional growth, or the ability to express certain proteins in their milk. Genetic engineering also plays a crucial role in medicine, with applications ranging from drug production and creating model animals that mimic human diseases to gene therapy (Harris & Gilbert, 2022).

One of the earliest breakthroughs in genetic engineering was the mass production of human insulin using genetically modified bacteria. This technology has since been expanded to produce human growth hormones, follicle-stimulating hormones (used to treat infertility), human albumin, monoclonal antibodies, antihemophilic factors, vaccines, and many other medications. Genetic engineering is also instrumental in creating animal models for studying human diseases, with genetically modified mice being the most widely used. These mice have been key in researching and modeling a variety of conditions, including cancer (like the oncomouse),

obesity, heart disease, diabetes, arthritis, substance abuse, anxiety, aging, and Parkinson's disease, which has greatly aided in testing potential treatments. Additionally, genetically modified pigs have been developed to increase the success of pig-to-human organ transplants.

12.3.1 *Transgenics Organisms and Its Types*

12.3.1.1 Plants

Transgenic crops that are resistant to specific herbicides, insects, or diseases are widely cultivated, particularly in the United States. Looking ahead, future transgenic plants are expected to have a much broader range of uses. They could be applied in areas like rangelands, forests, landscaping, nutrition, pharmacology, biological control, industrial chemical production, and environmental cleanup. Additionally, researchers are working on developing transgenic plants with improved resilience to various stresses, including abiotic ones like salinity, drought, and freezing, as well as biotic stresses from pathogens and human-induced challenges such as heavy metal pollution.

12.3.1.2 Viruses, Microorganisms, and Algae

Genetic modifications of viruses for environmental applications have mainly centered around baculoviruses. These naturally occurring viruses are already used for controlling insects biologically, and researchers are working to boost their effectiveness by adding genes that produce toxic proteins, such as scorpion toxins specific to insects. Transgenic bacteria and yeasts are commonly employed to produce biologically based products for medicine, food processing, and agriculture, like pesticides, though most of these products are made in controlled indoor settings. For instance, transgenic *Escherichia coli* that produce human insulin have largely replaced animal-derived insulin in medical treatments.

Genetically engineered bacteria are also used to produce rennet, a key ingredient in cheese-making used in the United States and elsewhere. Additionally, bovine growth hormone produced by transgenic bacteria has been used to increase milk production on many dairy farms in the US transgenic microorganisms are also being developed for cleaning up toxic substances. The cultivation of micro- and macroalgae is an important part of global aquaculture, and there is growing interest in creating transgenic algae for various applications, such as food, animal feed, polysaccharides like carrageenan, pharmaceuticals, fuel, and bioremediation.

12.3.1.3 Animals

Genetic engineering has been applied to animals to boost growth rates, enhance disease resistance, improve cold tolerance, produce organs for transplantation, and create biologically active therapeutic proteins. A lot of this research is still in its early stages. For example, fast-growing salmon are being tested to see if they can boost the production of farm-raised fish, to eventually bring them to market. By introducing growth hormone genes—often from the same species—researchers have achieved significantly faster growth rates in salmon, tilapia, and mud loach.

As we continue to discover more beneficial genes and refine techniques for integrating and reliably passing on these transgenes, the potential for genetic engineering across different types of life is expected to grow.

12.4 CRISPR/Cas9

CRISPR, a sequence of short, repeating nucleotides first discovered in bacteria and archaea, works with Cas proteins to eliminate foreign genetic elements (EGEs) (Srivastava & Raj, 2008). The process of removing these foreign elements involves three key steps: integrating new spacers, forming the CRISPR/Cas complex, and degrading the target. Initially, short sequences from invading DNA are added to the host's CRISPR loci as new spacers. Then, CRISPR RNAs (crRNAs) are produced to form a crRNA/Cas complex. Finally, this complex deactivates the foreign DNA by matching its sequence to the crRNA (Zhang et al., 2017).

So far, three types of CRISPR-Cas immune systems have been identified, each with distinct CRISPR repeat sequences and Cas protein profiles. Among them, the type II CRISPR-Cas9 system stands out as a powerful tool for genome editing in research and medicine. This system is particularly notable for using RNase III to transcribe crRNAs and requiring just a single Cas9 protein to form the crRNA/Cas9 complex. Almendros's team discovered the conserved NGG motif, known as the proto-spacer adjacent motif (PAM), by studying the CRISPR array of *Streptococcus pyogenes*. The CRISPR/Cas9 genome-editing system relies on guide RNA (gRNA) and the Cas9 nuclease. Unlike the original type II CRISPR-Cas system, this system uses a simplified gRNA structure that doesn't need the complex processing of crRNA. The gRNA is made up of a variable region and a basic scaffold (Croce et al., 2024). The variable region of the gRNA typically consists of 18–20 nucleotides that pair with the target DNA, while the basic scaffold is a longer RNA sequence that binds to the Cas9 nuclease, forming the gRNA/Cas9 complex (Fig. 12.2). This editing system also requires a PAM sequence, specifically NGG, which consists of three nucleotides. Only DNA with PAM sequences can be recognized and bound by the gRNA/Cas9 complex, leading to targeted double-strand breaks (DSBs). CRISPR technology is also being used to develop genetically modified crops that are resistant to diseases caused by bacteria, viruses, and fungi. For instance, CRISPR has been successfully applied to create rice varieties resistant to bacterial blight, a severe

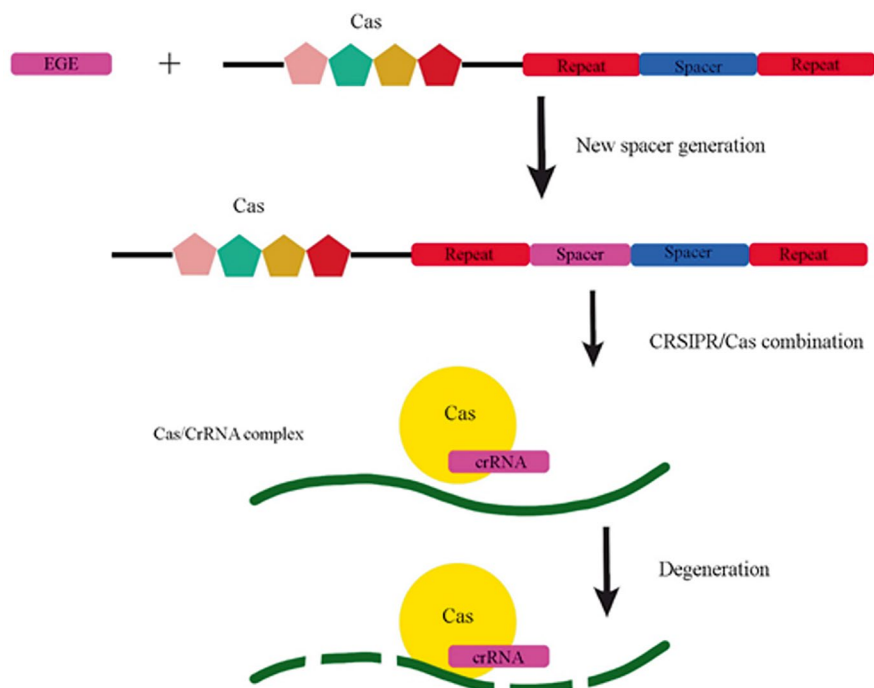


Fig. 12.2 “When exogenous genetic elements (EGEs) invade the host, some of their fragments integrate into the CRISPR loci as new spacers. These spacers are co-expressed with Cas nucleases to form Cas/crRNA complexes. During subsequent invasions, these complexes can recognize and bind to the same EGEs based on base complementation rules, ultimately leading to the degradation of the EGEs”

disease that threatens rice production (Santoso et al., 2022). Bacterial blight, caused by the bacterium *Xanthomonas oryzae*, poses a significant risk to rice crops, often leading to major yield losses. Traditional breeding methods to introduce resistance are often slow and less precise. However, CRISPR enables targeted modifications to specific genes involved in the plant’s immune response, making it a faster and more accurate approach to developing disease-resistant rice varieties.

In a notable example, researchers used CRISPR to modify the Xa13 gene in rice, which is crucial for the plant’s susceptibility to bacterial blight. By editing this gene, they developed rice plants that show enhanced resistance to the disease, improving crop protection and increasing yields. Moreover, CRISPR’s precision ensures that only the targeted traits are altered, without affecting other vital characteristics of the plant. This method not only enhances disease resistance but also supports sustainable agriculture by reducing the need for chemical pesticides (Pacesa et al., 2024).

12.4.1 Stem Cell Studies and Its Applications

CRISPR/Cas9-based gene manipulation techniques, including methods like gene knockout, gene knockin, gene interference, and activation, as well as various chromosome-related applications, have become essential tools in both biological and biomedical research. Stem cells are crucial for tissue repair and maintaining balance within the body (Puchta et al., 2022). In the realm of tissue repair and regeneration, stem cell-based therapies and gene therapy play central roles in modern medicine. Substantial investments of both human and financial resources in stem cell research have led to many notable advancements. CRISPR technology holds great promise for developing crops that are less susceptible to insect pests by targeting and editing genes associated with pest resistance. Such genetic modifications can help reduce the reliance on chemical pesticides, which often lead to environmental problems like soil and water pollution, damage to non-target organisms, and the rise of pesticide-resistant pest populations.

12.4.2 How CRISPR Enhances Pest Resistance

CRISPR can be used to knock out or alter genes in crops that make them susceptible to pests. For example, certain plants may have genes that produce compounds that attract pests. By editing these genes, scientists can reduce the plant's attractiveness to pests, thereby decreasing infestations. Scientists can introduce or enhance genes that provide natural resistance to pests. For instance, some plants produce certain proteins or secondary metabolites that are toxic to specific pests (Johnson & Pauwels, 2020). By enhancing these pathways through CRISPR, crops can be made more resistant to pest attacks. CRISPR allows for the simultaneous modification of multiple genes, which can be used to stack several resistance traits in a single crop. This multi-gene editing can provide robust protection against a variety of pests, reducing the need for multiple chemical treatments.

12.4.3 Drought Tolerance

Climate change is leading to more frequent and severe droughts, which pose a major threat to agricultural productivity, especially in arid and semi-arid regions. CRISPR technology offers a promising solution to this challenge by enhancing the drought tolerance of crops through precise gene editing. This involves targeting and modifying specific genes associated with water use efficiency and stress responses. CRISPR can be used to alter genes that control root growth and development (Kofler & Kraschel, 2018). Deeper and more extensive root systems enable plants to access water from deeper soil layers, improving their ability to withstand drought

conditions. For example, editing genes like DRO1 (Deeper Rooting 1) in rice has shown to increase root depth and improve drought tolerance. The stomata are tiny openings on plant leaves that regulate water loss through transpiration. By modifying genes related to stomatal development and function, such as EPF (Epidermal Patterning Factor), scientists can reduce water loss and enhance drought tolerance. This modification helps plants maintain water balance and continue photosynthesis during drought stress (Williams & Warman, 2017). CRISPR can enhance the production of osmoprotectants, which are compounds that help plants retain water and protect cellular structures during drought stress. For instance, altering genes responsible for producing proline, an osmoprotectant, can improve drought resistance in crops like wheat and maize. Drought stress frequently leads to the buildup of reactive oxygen species (ROS), which can damage plant cells. CRISPR can be used to enhance the activity of antioxidant enzymes such as superoxide dismutase (SOD) and catalase. These enzymes help neutralize ROS, protecting plants from oxidative stress during dry periods (“The Nobel Prize in Chemistry 2020 - Popular science background,” , 2020).

12.4.4 Case Studies and Applications

Researchers have used CRISPR to modify the OsNAC14 gene in rice, which is involved in the plant’s response to drought. The modified rice plants showed better drought resistance and higher yields even under water-scarce conditions. Likewise, in maize, CRISPR has been employed to tweak the ARGOS8 gene, which is known to inhibit ethylene responses related to drought sensitivity. The edited maize plants exhibited greater drought tolerance while still maintaining their yield levels.

12.4.5 Improving Photosynthesis

Improving photosynthesis through CRISPR technology offers a groundbreaking way to enhance crop growth rates and yields by optimizing the process plants use to convert sunlight into energy.

12.4.5.1 Optimizing Rubisco

Rubisco is the enzyme responsible for fixing carbon dioxide during the Calvin cycle. It is known for its inefficiency and tendency to fix oxygen instead of carbon dioxide, leading to photorespiration, which wastes energy. By using CRISPR to modify the genes encoding Rubisco, scientists can create more efficient versions of the enzyme that improve carbon fixation and reduce photorespiration.

12.4.5.2 Enhancing Light Capture

Photosynthetic efficiency can be increased by modifying the genes involved in light capture. For instance, genes that influence the size, number, and arrangement of chloroplasts (the organelles where photosynthesis occurs) can be edited to optimize light absorption. This ensures that plants can capture more sunlight and convert it into energy more efficiently.

12.4.5.3 Improving Electron Transport

The light-dependent reactions involve the transfer of electrons through the photosystems and electron transport chains (Gallo et al., 2018). By modifying genes that regulate the proteins and components of these systems, scientists can improve the efficiency of electron transport, resulting in higher production of ATP and NADPH, which are crucial for the Calvin cycle.

In summary, CRISPR technology enables scientists to edit genes that influence the photosynthesis process, leading to more efficient conversion of sunlight into energy. This genetic enhancement can significantly improve plant growth rates and crop yields, offering a promising solution for sustainable and resilient agriculture.

12.5 Bioinformatics and Computational Biology

Bioinformatics and computational biology are interdisciplinary areas that blend computer science, statistics, mathematics, and engineering to analyze and make sense of biological data. Machine learning algorithms can analyze extensive datasets of genetic sequences, experimental conditions, and transformation outcomes to discern patterns and predict the success of gene transformations. This assists researchers in optimizing experimental parameters, including vector design, promoter selection, and transformation protocols, thereby enhancing efficiency. When integrated with agricultural biotechnology, machine learning techniques provide substantial advantages for farmers by enabling them to implement highly targeted farming practices based on specific agroclimatic data.

12.5.1 Predicting Climate Impacts

Bioinformatics tools integrate diverse data sources, such as genomic data, climate data, soil conditions, and weather patterns. This holistic approach enables comprehensive analysis. Machine learning's ability to predict weather conditions enhances crop yield by allowing farmers to safely use vulnerable seeds through weather pattern analysis. Computational biology uses mathematical models and simulations to

predict how environmental changes, like temperature, precipitation, and CO₂ levels, affect crop growth. These models can forecast potential scenarios and outcomes. Early detection of drought, facilitated by AI-driven drought monitoring systems, can prevent severe losses and boost crop yields. Advanced machine learning techniques, such as Boosted Regression Trees (BRTs), have proven effective in linking crop yield with climate change (Ruffolo et al., 2024). BRTs offer greater accuracy than traditional Linear Regression (LR) methods by combining multiple regression trees through a popular ensemble approach called boosting. This technique trains several weaker trees sequentially to enhance the model's predictive accuracy and reduce the risk of overfitting. AI-driven weather forecasting in agriculture, when combined with satellite data, enables detailed examination of meteorological conditions, crop sustainability, and farm assessments for pests and diseases. AI tools provide precise information on temperature, wind speed, precipitation, and solar radiation (Peterson et al., 2018). This data helps farmers select and sow seeds under optimal conditions, leading to increased yields and reduced losses and time.

12.5.2 Designing Resilient Crops

Genomic analysis in bioinformatics involves examining the genetic material of crops to identify specific genes linked to traits that enhance resilience, such as drought tolerance, disease resistance, and heat tolerance (Benitez-Alfonso et al., 2023). By analyzing the crop's DNA, scientists can pinpoint the genetic variations responsible for these traits, which can then be targeted in breeding programs to develop crops that are better equipped to handle environmental stresses. Bioinformatics aids breeding programs by identifying genetic markers linked to desirable traits. These markers enable scientists to track and select plants with specific attributes more efficiently, accelerating the development of new crop varieties with enhanced resilience, such as better drought or disease resistance. Computational tools aid in designing accurate gene-editing strategies, such as CRISPR-Cas9, by predicting the best locations in the genome to introduce or modify traits. This precision enhances the effectiveness of gene editing in improving crop resilience against environmental stresses (Tripathi & Bisen, 2019). Studying gene expression under various environmental conditions reveals how genes respond to stress. This understanding of molecular mechanisms helps in developing crops with enhanced resilience by targeting specific genetic pathways involved in stress responses.

12.5.3 Robotics

Robotics technology has advanced significantly, offering versatility and flexibility that allow it to replace human labor. This shift reduces time and effort, avoids contact with hazardous substances, and greatly enhances safety (Beloiev et al., 2021).

As humanity faces the challenge of increasing agricultural production while minimizing environmental impact, robotics plays a crucial role. Modern farming has embraced automated machines, replacing traditional methods with more technical, precise approaches enabled by computer-aided tools like machine learning. This shift fosters precision farming and boosts agribusiness efficiency.

For example, robot scrapers used since 2013 have been effective in cleaning cattle walkways, which helps prevent infectious hoof disorders in cattle. In agriculture, robots provide numerous advantages, such as enhanced quality of fresh produce, reduced production costs, and decreased dependence on manual labor (Botta et al., 2022). They automate tasks such as weeding and spraying, particularly in scenarios where traditional machinery poses risks to operators.

12.6 Conclusion

Addressing the challenges in developing climate-resilient crops through biotechnology requires a holistic approach that integrates technical advancements, streamlined regulations, public engagement, ethical considerations, and economic support. By fostering collaboration and innovation across these areas, we can develop and deploy biotechnological solutions that boost agricultural resilience and maintain food security amid climate change.

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Chapter 13

Innovative Approaches to Alleviate Climate Stress in Crop Production



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13.1 Introduction

Climate change represents one of the most significant challenges confronting our planet in the present era. It is marked by substantial alterations in the average values of meteorological factors, including temperature and precipitation, over an extended timeframe (WMO & OMM, 1966). It has become evident that significant shifts in

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the global climate can be attributed to heightened human activities, leading to modifications in the composition of the Earth's atmosphere (Parry, 2007). Throughout the world, living organisms, including both plants and animals, have been affected by severe environmental conditions. The threat to global climate conditions has raised concerns, as fluctuations in diverse environmental factors could potentially jeopardize agricultural production, thereby threatening food security. Recent research has indicated that developed nations are more susceptible to climate change compared to developing countries (Altieri & Nicholls, 2017). In recent decades, there has been a rapid surge in scientific publications addressing the potential risks of climate change on agricultural production (Parajuli et al., 2019). Extreme climatic events can disrupt normal plant development, requiring the implementation of mitigation strategies to counteract their impact (Alotaibi, 2023). Devastating environmental changes have had a profound impact on natural ecosystems, agricultural yields, and human health (Alotaibi, 2023). As the global population rapidly expands, the growing need for food becomes a pressing concern due to apprehensions about the stability of the world's environment. Factors such as soil fertility air pollution and water availability exert a notable influence on farm productivity (Noya et al., 2018). As environmental conditions undergo sudden changes, significant impacts on vegetable productivity intensify due to both the direct and indirect effects of abiotic stress. The atmospheric concentration of CO₂ has risen from 280 to 400 μmol^{-1} , attributed to the excessive consumption of fossil fuels and ongoing deforestation. It is anticipated that this concentration will double, reaching 800 μmol^{-1} by the end of this century. Emissions of harmful gases, particularly CO₂, are the primary factors contributing to the greenhouse effect and the increase in global average temperatures (Vaughan et al., 2018). The evaluation of the impacts of climate change and environmental changes primarily involves evaluating their impacts on daily life, the frequency of stress periods, and the resulting damage to crops. In numerous countries, crop yields are predominantly affected by unfavorable environmental conditions. Consequently, the excessive accumulation of CO₂ and elevated temperatures has compelled researchers to address increasingly unpredictable challenges (Arunanondchai et al., 2018). To address these limitations and guarantee food security, it is imperative to embrace new varieties of crops that are climate-smart (Wheeler & Von Braun, 2013). Abiotic stress significantly impacts crop yield. In their natural climatic environment, plants commonly encounter various stresses, including drought, waterlogging, salinity, cold, and heat. Intense precipitation events have the potential to result in destructive flooding, while an extended period of insufficient or no precipitation can cause drought stress (Khan et al., 2016). Anomalies in precipitation exert direct adverse impacts on agricultural production, influencing both crop yields and the extent of cultivated land. There is evidence indicating that the approximately 9% increase in cropland in developing countries over the last two decades is a response to drought anomalies, with farmers expanding acreage to offset losses in yield (Zaveri et al., 2020). An emerging consensus suggests that existing agricultural practices are not sustainable, marked by the tendency to deplete valuable resources and cause environmental damage (FAO, 2016). These insights have triggered a paradigm shift in plant research and breeding approaches, emphasizing methodologies that empower plants to thrive while minimizing resource consumption. The aim is

for future crops to demonstrate enhanced efficiency in utilizing water and nutrients while sustaining yields in varied climatic conditions (Farhaoui et al., 2023). As per the IPCC-2014 report, the era spanning from the nineteenth to the twenty-first centuries is identified as the period characterized by the most significant warming (Pachauri et al., 2014). The Earth's environment is constantly changing, with industrialization being one of the main drivers of rising temperatures. Due to severe weather events, the impact of global warming is expected to intensify, ultimately disrupting ecosystems globally (Kanojia & Dijkwel, 2018). Crop yields are markedly affected by adverse weather conditions. Globally, the agricultural productivity of numerous crops has diminished as a consequence of rising temperatures. Towards the close of this century, a decline in global agricultural production is anticipated, correlating with an elevation in climate severity ranging from 2.6 to 4 °C. The drop in agricultural production represents a serious risk to food security, accentuated by the rapid growth of the world population (Zaveri et al., 2020). By 2050, food demand is anticipated to surge by approximately 85% in response to the projected global population rise to approximately 9 billion people, posing a significant challenge in meeting nutritional needs (Raza et al., 2019). The increased frequency of heavy rains and droughts, along with salinity and temperature instabilities, is anticipated to reduce agricultural production, thereby heightening the threat of famine (Dhankher & Foyer, 2018). Climate change and food insecurity stand out as primary challenges in the twenty-first century. Approximately 815 million people globally experience malnutrition, impeding sustainable development initiatives aimed at attaining the universal purpose of eradicating hunger by 2030 (Raza et al., 2019). The impact of climate change is worsened by contemporary cropping systems characterized by low diversity and a high concentration of inputs (Reckling et al., 2018). Approaches and measures aimed at substantially reducing the effects of climate change on crops, enhancing their adaptability to changing climates, and concurrently minimizing adverse effects are highly desirable. This study aims to provide insight into the effects of climate change on agricultural production. Additionally, the paper focuses on breakthrough solutions designed to alleviate the adverse impacts of climate stress on agriculture, with a particular emphasis on the need to overcome the obstacles that hinder sustainable and climate-smart cultivation. This includes a key focus on technical innovations within the field, covering advances in breeding techniques, digital agriculture and applications of artificial intelligence (AI). Through the integration of these technologies, producers can improve their adaptation capacities, thereby ensuring more resilient and efficient agricultural yields in the face of the challenges presented by climate change.

13.2 Climate Stress in Crop Production

Climate change is a subject of heightened concern, with far-reaching implications for agricultural systems that require serious consideration. The escalating temperatures contribute to increased unpredictability in weather patterns, giving rise to more increased frequency of extreme events, such as floods and droughts, and

imposing substantial stress on various crop species (Shahzad et al., 2021). The resultant climate stress represents a momentous and pressing challenge that exerts a profound influence on global crop production (Gray & Brady, 2016). With the continued evolution of climate change, farmers and agricultural experts have been confronted with the daunting task of comprehending and mitigating the adverse impacts of climate stress on crops.

The term “climate stress” encompasses adverse conditions that crops endure due to fluctuations in temperature, precipitation patterns, humidity levels, and extreme weather events (Acharya et al., 2023). These stressors can detrimentally affect crop yields (Table 13.1), heighten vulnerability to diseases and pests, and create instability in agricultural systems (Acharya et al., 2023).

By studying the specific environmental factors that contribute to climate stress, researchers can formulate strategies to adapt crops and implement sustainable practices, thereby minimizing their impact. Comprehending the diverse responses of crops to climate stress is pivotal for breeding programs aimed at cultivating resilient crops. Identifying genetic traits associated with tolerance or resistance to specific stressors enhances crop resilience and productivity, particularly in challenging environments (Raza et al., 2019).

Table 13.1 Examples of the impact of various environmental stress factors on yield losses in major crop species stress

Crop species	Stress	Yield losses (%)	References
Chickpea (<i>Cicer arietinum</i> L.)	Drought	20–50	Alamin and Abdalla (2020)
	Heat	39	Devasirvatham et al. (2015)
	Cold	15–20	Chaturvedi et al. (2009)
	Flooding	88 (plant biomass)	Dron et al. (2021)
Rice (<i>Oryza sativa</i> L.)	Drought	53–92	Lafitte et al. (2007)
	Heat	50	Li et al. (2010)
	Flooding	3	Kim et al. (2023)
Wheat (<i>Triticum aestivum</i> L.)	Drought	57	Balla et al. (2011)
	Heat	31	Balla et al. (2011)
	Cold	10	Li et al. (2022)
	Flooding	2	Kim et al. (2023)
Maize (<i>Zea mays</i> L.)	Drought	63–87 28–55	Kamara et al. (2003), Mugo and Pathaka (2012)
	Heat	20	Dhaliwal and Williams (2022)
	Cold	18–28	Žydelis et al. (2018)
	Flooding	1 5–30	Kim et al. (2023) Kumar et al. (2009)
Soybean (<i>Glycine max</i> L.)	Drought	73–82	Wei et al. (2018)
	Heat	2–10	Schauberger et al. (2019)
	Flooding	4	Kim et al. (2023)
Sunflower (<i>Helianthus annuus</i>)	Drought	60	Mazahery-Laghab et al. (2003)
	Heat	14–34	Debaeke et al. (2017)

Briefly, the agricultural sector faces unprecedented challenges owing to the escalating prevalence of climate stress induced by a changing climate. Understanding the multifaceted nature of climate stress and its profound implications on crop physiology and agricultural productivity is crucial for devising effective mitigation strategies. This section explores the intricate facets of climate stress, including an examination of its contributing factors, insights into its general impacts on plant physiology and yields, an evaluation of traditional mitigation approaches, and a strong emphasis on the urgent need for innovative strategies to fortify agricultural resilience amidst dynamic climatic conditions.

13.2.1 Key Factors in Climate Stress for Crops

Climate stress presents a dynamic amalgamation of environmental factors that profoundly affect crop growth and development. Elevated temperatures, erratic alterations in precipitation, prolonged droughts, intensified extreme weather occurrences, and shifting pest and disease dynamics are pivotal components that contribute to the complexity of climate stress in agricultural ecosystems (Abobatta, 2023). The responses of various crops to these stressors vary significantly, underscoring the need for tailored assessments specific to each crop variety (Table 13.1).

Efficiently tackling climate stress in crop production hinges on a comprehensive understanding of its causes and ramifications. Delving into the specific environmental factors that contribute to climate stress empowers researchers to devise strategies for crop adaptation and the implementation of sustainable agricultural practices aimed at mitigating its impact (Chachar et al., 2023).

The multifaceted nature of these stress factors necessitates comprehensive and nuanced strategies tailored to individual crop species, thereby enabling proactive mitigation of the adverse impacts of climate stress in agriculture (Gakpey, 2022). Integrating empirical observations with advanced technological tools allows for a deeper insight into these stressors, facilitating the development of adaptive strategies that augment crop resilience and ensure sustainable agricultural productivity in increasingly volatile climates (Gakpey, 2022).

13.2.2 Impacts on Plant Physiology and Yields

Comprehending plant physiology is crucial for grasping how plants respond to climate stress, thereby guiding the development of strategies for enhancing crop resilience. Various environmental stressors elicit specific physiological responses in plants, including alterations in gene expression, metabolic pathway adjustments, and modifications in phenological stages, which significantly affect crop yield and quality (Fahad et al., 2017). Temperature is a crucial environmental factor that profoundly influences plant development and growth, affecting key processes, such as

photosynthesis, transpiration, respiration, germination, and flowering. Exposure to elevated temperatures initiates a cascade of physiological changes, activating defense mechanisms such as heat shock proteins and antioxidants (Ul Hassan et al., 2022). Prolonged exposure may result in diminished photosynthesis, increased respiration rates, and irreversible damage to plant tissues, ultimately leading to reduced yield (Sharma et al., 2022). Elevated cellular temperatures induce mitochondrial swelling, reduced respiration due to an increased ATP: ADP ratio, impaired ATP transfer mediated by abscisic acid, disturbance in tricarboxylic acid (TCA) cycle intermediates, lipid peroxidation in mitochondrial membranes, and initiation of programmed cell death through the release of cytochrome *c* (Bhattacharya, 2022). Depending on the specific plant and circumstances, temperature variations can either accelerate or decelerate the transition from vegetative to reproductive growth (Bhattacharya, 2022).

The temperature required for germination varies among species; nevertheless, for optimal germination, most crop seeds prefer temperatures ranging from 15 to 30 °C (Farooq et al., 2022). Extreme temperatures induce stress, potentially causing nutrient deficiency, and adversely affecting plant physiology and yield (Sehgal et al., 2018). Additionally, plants in containers may die if their roots are exposed to temperatures above their tolerance threshold (Marchin et al., 2022).

Low daytime temperatures not only result in reduced yield, including decreased fruit or grain production, but also contribute to poor plant growth. Cold temperatures adversely affect plant physiology (Bhattacharya, 2022). Frost and freezing conditions induce cell membrane damage, disrupt water transport, and impair photosynthesis, resulting in decreased growth, delayed flowering, and potential plant mortality, thereby causing substantial yield losses (Román-Figueroa et al., 2021). Certain plants in cold regions require a specific duration of low temperatures for dormancy. These plants can enhance their freezing tolerance through cold acclimation, responding to low temperatures via changes in gene expression and protein synthesis (Bhattacharya, 2022). Tropical and subtropical crops are vulnerable to injury or death due to non-freezing low temperatures, whereas plants from temperate climatic regions are considered chilling-tolerant to varying degrees compared to tropical and subtropical crops (Goswami et al., 2022). A decrease in temperature triggers hormonal changes in plants, leading to the formation of an abscission layer, where each petiole joins a stem, resulting in leaf shedding (Ashraf et al., 2023). Understanding the effect of temperature on plant development and growth is crucial, and manipulating the temperature can be instrumental in enhancing leaf, flower, and fruit production.

Drought stress, arising from an inadequate water supply, prompts diverse plant responses, including stomatal closure to minimize water loss, altered root growth to access deeper soil water, and adjustments in leaf structure to reduce water loss (Gupta et al., 2020). Water stress in plants elicits a diverse range of adverse effects including reduced photosynthesis, lipid peroxidation, protein mutations, DNA damage, cell death, and diminished transpiration. Concurrently, it triggers adaptations such as leaf shedding and permanent wilting, instigating modifications in the root and shoot systems that ultimately result in decreased plant yield (Barnawal et al.,

2019). Despite being crucial for survival, these responses can negatively affect yields by diminishing photosynthesis and nutrient uptake (Gupta et al., 2020). Water stress significantly affects global crop production, with various factors influencing crop yields (Seleiman et al., 2021).

Soil waterlogging caused by flooding damages most crops and negatively affects crop production, especially dryland species (Manik et al., 2019). Common consequences of waterlogging on crops include energy depletion within plant cells, limited photosynthetic activities, and stunted growth or death of plant shoots and roots (Sharma et al., 2021). Hypoxia and anoxia occur because oxygen levels limit mitochondrial respiration, leading to complete inhibition of respiration (Sharma et al., 2021).

Moreover, drought followed by heavy rainfall can heighten the risk of flooding, which creates favorable conditions for fungal infestations on roots, leaves, and tuber crops (Liliane & Charles, 2020). Water stress restricts gas diffusion between plants and their surroundings, leading to the buildup of high levels of ethylene and CO₂ in the root zone, accompanied by very low O₂ (Sharma et al., 2021).

In brief, climate stress directly disrupts plant physiological processes, resulting in diminished growth and development, and ultimately lower crop yields. Furthermore, it influences plant-pathogen interactions, rendering plants more susceptible to diseases under stress conditions and impacting their ability to produce optimal yields. Understanding the intricate relationships between stressors and crop responses is pivotal for devising effective adaptation measures against the consequences of climate change on agriculture. Heavy climatic events induced by climate change can have negative effects on soil health and quality, leading to reduced nutrient availability for plants. Therefore, it is important to further investigate the impacts of climate stress on plant nutrient uptake and utilization to develop effective strategies to alleviate its effects on crop production.

13.3 Traditional Approaches to Mitigating Climate Stress

Amidst the challenges posed by climate stressors, some traditional methodologies have served as a cornerstone for alleviating their impacts on crop cultivation, ensuring the continuity of agricultural productivity. However, the efficacy and constraints of conventional techniques underscore the need for pioneering solutions to combat climate-induced stress on crops effectively. This segment delves into some traditional methods employed to assuage climate stress, scrutinizes the impediments and boundaries inherent in these practices, illustrates exemplary instances of triumph, and accentuates the significance of adopting cutting-edge technologies and resilient agricultural practices to steer the course towards a sustainable agrarian future (Fig. 13.1).

Traditional knowledge held by indigenous communities is often undervalued; however, it is crucial in addressing climate change. Traditional methods employed to alleviate climate stress on crops include well-established practices such as

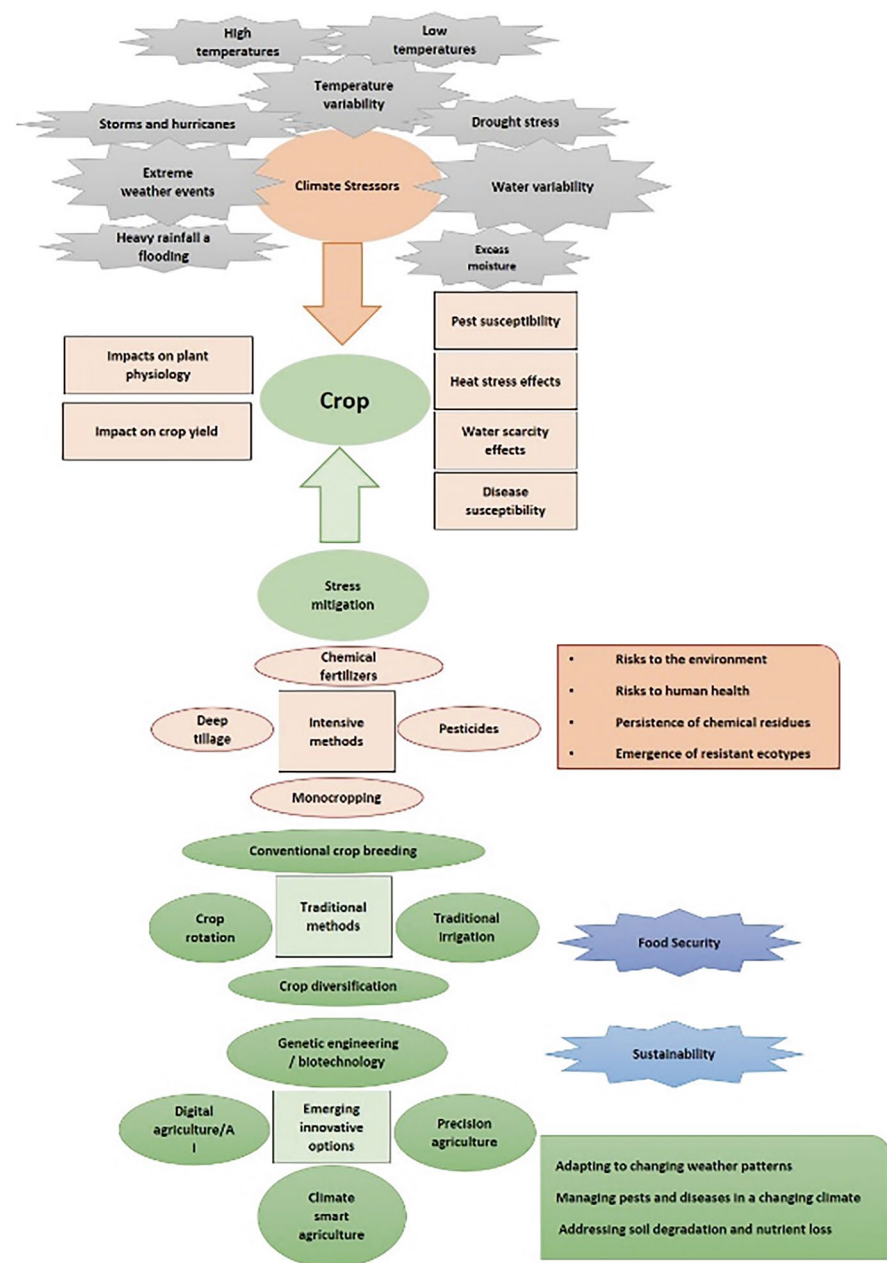


Fig. 13.1 Navigating climate stress in agriculture between traditional and innovative approaches

conventional crop breeding and selection, enhanced water management and irrigation strategies, and the implementation of crop rotations and diversification (Qaim, 2020). These time-honored methods, refined over centuries, have proven instrumental in fortifying crop resilience and enhancing productivity in response to the evolving environmental dynamics. Farmers, drawing on their extensive experience in facing challenges, utilize a repertoire of traditional techniques to combat climate stress (Papa et al., 2020).

Climate change-induced water stress presents a formidable challenge for water management and irrigation in agriculture, necessitating innovative sustainable strategies. Recognizing the pivotal role of water in plant growth during unpredictable rainfall patterns has led to the development of innovative solutions (Mishra et al., 2021). Their adaptation includes efficient irrigation systems, rainwater harvesting, precision-based techniques, and adept resource management (Pandya et al., 2021). While traditional methods such as enhancing irrigation efficiency, altering crops, and establishing sustainable systems remain valuable, integrating nature-based solutions, such as contour stone bunds and terracing, holds promise in alleviating crop water stress and enhancing soil moisture retention critical elements for climate-resilient agriculture (Chawla & Balasaheb, 2023). However, global irrigation of biomass plantations for bioenergy could exacerbate water stress more than climate change alone (Stenzel et al., 2021). Therefore, understanding crop water requirements is imperative for enhancing water utilization efficiency in irrigated agriculture, considering the looming effect of climate change on irrigation needs and crop productivity (Chawla & Balasaheb, 2023).

Embracing the potential of diversity remains paramount. Similar to a varied cohort navigating challenges adeptly, farmers harness the strength of biodiversity by cultivating an array of crops and implementing strategic crop rotations (Bowles et al., 2020). This diversified approach helps mitigate the impact of climate stress by curbing crop vulnerability to pests and diseases, thereby fostering soil vigor and health (Hufnagel et al., 2020). Crop rotation and diversification are effective measures to reduce climate stress in agriculture (Bowles et al., 2020). Crop rotation, by changing farming systems, reduces the exposure of a particular crop to extreme weather conditions, thereby lowering the risk of crop failure. It enables crops to withstand abiotic stresses under harsh growing conditions such as drought. Dynamic adaptation to different climatic conditions contributes to increased resilience, disease resistance, and improved productivity (Rolo et al., 2023).

Continuous crop rotation significantly enhances soil properties, especially organic carbon content, thus strengthening the system against crop losses during drought conditions. A 3-year rotation of wheat and maize has been emphasized as an effective strategy for improving crop fatigue resistance (Boutagayout et al., 2023a). Additionally, Altieri and Nicholls (2017) noted that increasing crop diversity involves no trade-offs between measured ecosystem functions and blunts the link between stress resistance, pest management, and crop production. Thus, crop rotation and intercropping have emerged as essential agricultural strategies to improve soil health, enhance crop resilience, and protect crops from adverse weather conditions, ultimately reducing climate stress (Boutagayout et al., 2023a).

In addition, alternative traditional strategies have been proposed within the agroecological framework as sustainable approaches to mitigate the impacts of climate stress (Boutagayout et al., 2023b). Agroecological practices epitomize the collaborative fusion of traditional wisdom and contemporary science, aiming to yield a diverse array of benefits spanning health, nutrition, environmental sustainability, spirituality, and socioeconomic aspects (Romero et al., 2022). These practices intricately focus on the management of soil, water, and crops within agroecosystems, resulting in a nuanced classification owing to their multifaceted advantages. Crop management practices, with a pivotal emphasis on diversification, actively counteract biodiversity loss and alleviate dependence on nonrenewable resources, thereby enhancing resilience in the face of climate uncertainty (Tomich et al., 2011). Techniques, such as agroforestry and crop association, play a pivotal role in augmenting ecological processes, thereby bolstering overall agricultural productivity. Soil management practices, including the use of organic biofertilizers and cover crops, significantly contribute to sustainable soil management by mitigating erosion, enhancing nutrient content, and improving soil structure (Romero et al., 2022). Similarly, water management practices are intricately interwoven with soil management, underscoring the significance of strategies such as compost application and organic mulching in enhancing water availability and retention (Boutagayout et al., 2023b). Pest management within an agroecological framework prioritizes a range of alternatives, including light, cultural, biological, manual, and chemical control methods, fostering biological regulation and interactions to effectively address pest challenges (Brzozowski & Mazourek, 2018). The deliberate utilization of diverse plant species, allelopathy, and crop diversification further fortify agroecological defenses against pests through intricate ecological processes and systems (Romero et al., 2022).

13.4 Innovative Breeding Techniques

Conventional breeding methods have shown their effectiveness in the past, particularly in improving agronomic traits. However, facing the challenges presented by climate change and increasing nutritional needs, conventional breeding faces limitations such as genetic and reproductive barriers (Kitashiba & Nasrallah, 2014), genetic drag, and the difficulty in combining multiple desired alleles for complex traits (Lyzenga et al., 2021). These limitations have been overcome by the emergence of advanced gene editing techniques, enabling targeted manipulations in a variety of cells and organisms.

13.4.1 New Genetic Engineering Technologies for Crop Resilience

13.4.1.1 Sequence-Specific Nuclease

The initial programmable nucleases employed in plants were small meganucleases, with a size of around 165 amino acids, designed to target brief DNA sequences of more than 12 base pairs (Miller et al., 2007). Among these, zinc finger proteins (ZFNs), discovered in 1983, have been used to specifically bind DNA sequences of 12–18 bp, appropriate for the majority of techniques used in plant transformation (Segal et al., 2003). Although the ZFN method has contributed to improving research in applied biotechnology, it presents challenges such as its high cost, toxicity, and susceptibility to inaccurate recognition of DNA sequences in plants (Miller et al., 2007). In 2009, transcription activator-like effector nucleases (TALENs) were discovered as a targeted alternative to a specific DNA domain (Boch et al., 2009). However, their synthetic complexity due to the repetitive nature of their DNA-binding domains has limited their precision and targeted cutting efficiency. Cloning methods based on multiple assemblies, such as Golden Gate cloning, have partially solved this problem (Engler et al., 2014). However, the advent of newer technologies such as CRISPR/Cas has rapidly replaced the use of TALENs due to their simple, rapid, and precise design (Belhaj et al., 2015). There are several categories of CRISPR systems, types I, II, and V cut DNA, while type VI cleaves RNA and type III cleaves both RNA and DNA (Hillary & Ceasar, 2023). Cas proteins, together with CRISPR, act in tandem with gRNA to specifically target specific domains in DNA. There are several types of Cas proteins, Cas9, Cas10, Cas12, Cas13, and Cas14 (Hillary & Ceasar, 2023) serving as an easily manageable and resilient gRNA-guided DNA targeting tool has found extensive application in plant biology. It has been utilized for diverse purposes such as enhancing agronomic traits, fortifying disease resistance, and improving nutritional quality (Hillary & Ceasar, 2023).

13.4.1.2 Genome Engineering at the Transcription Level

Promoters, whether natural or artificial, play an important role in plant breeding as key elements governing gene expression. In the promoter region, a diversity of reactive elements has been identified, capable of initiating transcription in response to various stresses, whether biotic or abiotic (Zhu et al., 2018). These mechanisms are widely exploited in plant breeding programs aimed at introducing beneficial traits such as disease resistance, abiotic stress tolerance, and yield optimization. The RNA interference (RNAi)-based gene silencing method represents a powerful post-transcriptional approach to specifically regulate gene expression (Ashfaq et al., 2020). Previous investigations have confirmed the success of using RNAi to enhance plant resistance to pathogens or to regulate the synthesis of specific metabolites in plants (Sargent et al., 2022). Although RNAi offers significant advantages in plant

breeding, challenges remain, such as the long-term stability of the silencing effect and targeting specificity. Another emerging approach in transcriptional regulation is epigenome editing, which combines engineered genome editing machinery with the CRISPR/Cas system, known as CRISPR interference (CRISPRi) (Rai et al., 2019, p. 20). This method has demonstrated the ability to significantly repress gene expression, achieving suppression rates ranging from 60% to 99.9% (Sargent et al., 2022).

13.4.1.3 Engineering at the Translational Level

Plant engineering at the translational level involves the application of engineering principles to manipulate biological processes during the translation of genetic information into functional proteins. This field focuses on the modification and optimization of protein synthesis from plant messenger RNA (mRNA) to achieve desired characteristics (Zhang et al., 2018). Approaches such as codon optimization, mRNA editing, ribosome engineering, RNA interference, and synthetic biology are used to precisely regulate the level of translation (Tan et al., 2020). The CRISPR/Cas system is an ideally effective way to manipulate splicing outcomes (Tan et al., 2020). The use of CRISPR-directed base editors to manipulate pre-mRNA splicing is anticipated to find applications in the functional examination of mRNA isoforms in cultured environments (Zhang et al., 2018). These techniques make it possible to control the efficiency of protein synthesis, adjust the abundance of specific proteins, and introduce foreign genes to produce proteins with beneficial properties. Plant engineering at the translational level offers significant potential to improve crop yields, enhance stress resistance, and develop plants with improved agronomic traits.

13.4.2 Assessing the Ethical and Scientific Implications

13.4.2.1 Scientific Implications

Applications of innovative genome editing approaches in plants have opened up exciting new perspectives, accelerating the creation of varieties that resist disease, tolerate adverse environmental conditions, and exhibit improved nutritional profiles.

13.4.2.1.1 Improve Productivity

The CRISPR/Cas9 system has proven to be a powerful tool to significantly improve the yield of various crops, including rice, tomato, wheat, rapeseed, soybean, and ground cherry (Yuan et al., 2023). Extensive investigations have been carried out to specifically target genes and metabolic pathways responsible for carbon dioxide assimilation, such as Rubisco and the cytochrome b6f complex (Yuan et al., 2023).

Recent studies highlight notable advances in genomic engineering aimed at improving crop productivity, as evidenced by the review work of Van Esse et al. (2020) and Gao (2021). This research highlights the considerable opportunities offered by genome editing to tackle the growing challenges associated with food security and agricultural sustainability.

13.4.2.1.2 Improve Resistance to Biotic Stress

The RNAi technique has demonstrated its effectiveness in the targeted control of insect pests in various crops (Yuan et al., 2023). At the same time, gene drives have been successfully applied to restore pesticide-resistant insect populations to susceptibility levels (Chambers et al., 2016). The synergistic integration of RNAi, CRISPR-Cas9, and TALENS technologies has proven to be a particularly successful approach to confer resistance against fungal and bacterial infections (Li et al., 2020). The CRISPR/Cas9 system has been utilized to bolster disease resistance in vital crops, including tomato potato, wheat, and rice, along with oilseed and fruit crops (Nerkar et al., 2022). More specifically, the introduction of powdery mildew resistance in wheat was successfully achieved using CRISPR/Cas9. Resistance to viral infection was enhanced using CRISPR/Cas9 and CRISPR/Cas13 (Yuan et al., 2023) in previously susceptible plants. These advances demonstrate the versatility and power of modern genetic techniques to strengthen crop resilience in the face of phytosanitary challenges.

13.4.2.1.3 Improve Resistance to Abiotic Stress

Promoters play a crucial role in plant improvement by introducing desired traits, such as tolerance to environmental stresses. Promoters governing gene expression in response to abiotic and biotic stress have been thoroughly discussed. CRISPR/Cas9-induced mutations have also been employed to increase tolerance to salinity and drought (Yuan et al., 2023). CRISPR/Cas9 is effective in enhancing drought stress tolerance in various crops, including tomatoes, petunias, citrus, grapes, potatoes, and apples (Farooq et al., 2021). Meanwhile, studies indicate that expression modulation and overexpression of aquaporins represent promising strategies for the development of water-saving and drought-tolerant crops (Ermakova et al., 2021). Other approaches, such as the application of chemical priming agents and genetic engineering, have the potential to augment the regulatory and functional genes of plants, leading to an enhancement in their stress tolerance (Yuan et al., 2023). Recent advances in the use of gene editing systems to enhance tolerance to abiotic stresses, such as salinity, drought, heat, cold, high pressure, and metals, were recently outlined by Yadav et al. (2023).

13.4.2.1.4 Improve Nutrient Use Efficiency

The overuse of fertilizers is proving harmful to the environment while consumer interest in more eco-friendly products is growing. Furthermore, this practice proves to be unsustainable due to the increasing costs of fertilizers, their low efficiency of use, and the limited availability of crops (Perchlik & Tegeder, 2017). To meet this challenge, it is possible to improve the efficiency, assimilation or absorption of nutrients by crops. The integration of enzymes like nitrogenases or phytases into plants could be implemented to facilitate the fixation of crucial nutrients (Allen et al., 2020). The possibility and limits of engineering aimed at improving the assimilation of fertilizers by plants have been explored in several review articles (Sargent et al., 2022).

13.4.2.1.5 Improve Nutritional Quality

Genome editing techniques can be harnessed to enhance the nutritional quality of plants, thereby playing a crucial role in ensuring food security. Various studies have demonstrated the ability to increase ϵ -carotene content, overall levels, vitamin C concentration, and oil content through the use of CRISPR. Summary articles, bringing together several results on improving nutritional quality through innovative techniques, have been published (Sahoo & Panda, 2023).

13.4.2.2 Ethical Implications

Innovative genome editing techniques offer promising prospects in agriculture and food security; however, they also raise significant ethical concerns. Plants resulting from biotechnology have been the subject of extensive study and debate over their environmental impact, intellectual property, the seed industry, and consumer distrust. A major concern is the potential impact on biodiversity and ecosystems, requiring rigorous ecological risk assessment before releasing edited plants into the wild (Tsatsakis et al., 2017). Contrary to initial expectations, transgenic tools have contributed to unprecedented genetic homogeneity in industrial crops (Bošković & Žuža, 2019), with a widespread spread of transferred genes causing global genetic pollution (Tsatsakis et al., 2017). Incorrect identification of favorable alleles can also induce the unintended spread of undesirable mutated traits through gene drives, necessitating a thorough risk assessment before containment. Ethical concerns related to food safety are also emerging, particularly concerning genetic modifications impacting the nutritional composition of edited plants, requiring rigorous assessment of the effects on human health.

Furthermore, ethical considerations regarding intellectual property and farmers' rights are at the heart of debates, with patents potentially accentuating inequalities and restricting access to modified seeds, especially in developing regions (Kour et al., 2022). The application of genome editing can also lead to economic

disparities between large and small farms. Regulatory frameworks must balance the industry's needs for new technologies and community concerns. However, regulations vary considerably between countries and struggle to quickly adapt to advances in genetic technologies. Two regulatory approaches dominate (Vega Rodríguez et al., 2022): the first, adopted by the Court of Justice of the European Union, assesses the risks linked to the production procedure of the final product, while the second, adopted by Canada, the United States, and Argentina, focuses on the assessment of product risks on health and the environment. However, the application of these regulations can have direct implications on the commercialization of genetically edited plants and hinder scientific advances due to financial disengagement in the submitted research (Kour et al., 2022).

13.5 Precision Agriculture

Precision agriculture (PA) has become a vital strategy for managing geographical and temporal variations in agricultural fields, especially in light of the forecast of a world population of 9–10 billion by 2050. To increase global food production by at least 70% by the same period, PA becomes crucial to contemporary agricultural research (Liu et al., 2020). This approach responds to a major challenge: increasing production while diminishing the use of inputs, lowering environmental pressures, and ensuring sustainability (McFadden et al., 2023). Born in the 1990s with the introduction of GPS, GIS, yield monitors, and other technologies, PA has evolved with the industry 3.0 era, moving from predominantly manual use to advanced digitization. Technologies such as variable rate technologies, electronic maps, and yield monitors have become commonplace, enabling farmers to make informed decisions based on high-resolution data collected via remote sensing technologies such as satellites and drones (Liu et al., 2020). PA now encompasses not only agricultural crops but also other agricultural production systems, such as agronomy, livestock, agroforestry, and aquaculture.

Data collection and the use of decision support tools are essential elements in identifying and analyzing various aspects of agriculture. In the context of precision agriculture, data on fields and individual crops are gathered through a variety of sensors, yield monitors, soil monitoring devices, as well as through remote sensing technologies such as aerial or satellite imagery (Hundal et al., 2023). This detection process forms a fundamental pillar of precision agricultural management, enabling farmers to obtain detailed data on climatic conditions, soil health, water availability, fertilizer requirements, pest and disease threats, and other factors (McFadden et al., 2023). Sensors play a crucial role in gathering information such as crop biomass, thereby guiding decisions regarding fertilization and crop maintenance. Yield monitors, equipped with mass flow and humidity sensors, as well as a differential Global Positioning System (GPS), provide real-time accurate information, allowing farmers to identify areas requiring specific interventions, such as fertilization (Hundal et al., 2023).

Remote sensing technologies, including aircraft, drones, ground sensors, and satellites, are employed to collect data on crop and soil conditions. Remote sensing facilitates the detection of spatial patterns of plant signatures that correspond to soil properties and detects stresses caused by pests or diseases. Imagery, as a form of remote sensing data, can provide ground truth verification (Haneklaus et al., 2016). Previously, aircraft were used not only for various agricultural imaging operations but also for fertilizer or chemical spraying. Satellite imagery has been available for farm management for several years; for example, US-LANDSAT satellites have been used for this purpose since 1970. Unmanned Aerial Vehicles (UAVs) equipped with Global Navigation Satellite System (GNSS) technology have recently been used for mapping, imagery data collection, surveying, crop spraying, and livestock monitoring fertilization (Hundal et al., 2023). Geocoded sampling is vital for precision agriculture and ground truth verification when spatial images are utilized for decision-making. Real-time and cost-effective remote sensing technologies, such as LASSIE (Low Altitude Stationary Surveillance Instrumentation Equipment), are critical in precision agriculture. They enable continuous and automated recording of real-time crop and soil images with GIS references (Haneklaus et al., 2016).

Data captured by sensors, along with other data related to the geospatial coordinates of a global navigation satellite system (GNSS), provide crucial information for the creation of maps, including soil maps and yield maps, used in site-specific decision-making (McFadden et al., 2023). Yield maps enable quantitative and qualitative characterization of field production, which is essential for guiding management decisions. Analyzing variations depicted on these maps helps identify factors influencing productivity, thus assisting in the implementation of site-specific management strategies. Soil maps provide valuable information on the spatial distribution of physical and chemical properties within a field, serving as critical tools for decision-making in precision agriculture. (Hundal et al., 2023). This importance arises from the influence of soil chemical and physical characteristics, such as nutrient retention capacity, water retention, porosity, bulk density, topography, and nutrient availability, on crop yield. Additionally, climate trends and weather can be anticipated using data captured by sensors, which is crucial for all agricultural practices (McFadden et al., 2023).

Variable rate technologies (VRT) in precision agriculture entail the application of inputs (Table 13.2) such as fertilizers, water, seeds, and crop protection chemicals (herbicides, pesticides) at rates that vary according to the specific needs of each zone within a field (Hundal et al., 2023). This approach aims to reduce chemical residues and resource wastage while improving net profit through enhanced crop yields and decreased input costs. Growers can thus utilize resources according to the specific needs of each zone within the field, thereby avoiding uniform application of products across the entire field (Walter et al., 2017).

Table 13.2 Example of technology applications in precision agriculture and CSA practices

Technology used	Application	References
GNSS	Classify field roads based on GNSS data from agricultural machinery using pixel-level visual characteristics	Chen et al. (2023b)
GPS, soil data maps, IoT, yield data maps	A technique for integrating yield and soil sensor maps through data fusion	Karunathilake et al. (2023)
VRT	A method involving multisensor data fusion to generate variable depth tillage zones	Karunathilake et al. (2023)
Agricultural robots	Creating and developing a robot to apply pesticides and fertilizers in agriculture	Ghafar et al. (2023)
Water management system using satellite LANDSAT data and meteo-hydrological modeling	Designing and implementing an efficient irrigation system for water resource management	Corbari et al. (2019)
Drone-based imaging spectrometry and photogrammetry	Managing and monitoring the quantity and quality of grass swards utilized in silage production	Oliveira et al. (2020)
Improved organic fertilizer mixer based on the Internet of Things (IoT)	Monitoring the fertilizer production status remotely and delivering updates and alerts to farmers	Ishak et al. (2023)
IoT-based fertigation system	Providing economic and environmental benefits surpassing empirical models	Lin et al. (2020)
Computer vision, DL, IoT, smartphone	Computer Vision and Deep Learning-based Model for Weed Detection	Punithavathi et al. (2023)
ML and ANN models	Innovation in common bean breeding through a combined approach of in vitro regeneration and Machine Learning algorithm citation	Aasim et al. (2022)
IoT, agricultural robotics, blockchain technology with hyperledger fabric platform	Utilizing smart contracts with FCG for dynamic robot coalition formation	Filipe et al. (2020)

13.6 Climate-Smart Agriculture Practices

Climate-Smart Agriculture (CSA) is committed to restructuring agricultural development to tackle the challenges presented by climate change (Zhao et al., 2023). By fostering synergies at different scales, CSA aims to strengthen connections among local, national, and global agricultural stakeholders to accelerate adaptation and mitigation efforts (Adger et al., 2005). As a result, CSA offers a triple benefit by enhancing agricultural production productivity, income, and resilience to climate change while reducing or even eliminating greenhouse gas emissions. It thereby offers a holistic solution to the challenges encountered by global agricultural development (Thornton et al., 2018). Practices within the scope of CSA, such as enhanced water management, plant breeding, and conservation agriculture, have demonstrated their ability to boost income, productivity, and food security in diverse regions, according to several scientific studies (Zhao et al., 2023).

Among the practical applications used in CSA, the Internet of Things (IoT) represents a collection of computer devices, sensors, and machines connected to the Internet, thus forming an interconnected network (Zhao et al., 2023). In the agricultural context, IoT is widely utilized for data collection from various sensors, including monitoring environmental parameters and crop conditions such as humidity, temperature, soil pH, and plant health (Islam et al., 2021). Numerous applications of IoT in agriculture have been explored (Table 13.2), including the evaluation of various applications of this technology and the development of specific architectures for food monitoring (Dias et al., 2020). Furthermore, the integration of IoT with the use of agricultural drones is also being studied within the framework of smart agriculture (Islam et al., 2021).

The integration of AI represents a promising perspective for smart agriculture. AI, using digital computers or other controlled machines, aims to mimic, extend, and develop human intelligence by perceiving the environment and pertinent relevant knowledge. In many sectors, AI has already proven significant benefits (Subeesh & Mehta, 2021). Recent advancements in computer hardware and big data have paved the way for the application of AI in the agricultural domain. Currently, AI is widely used in various aspects of agriculture, including plant recognition, crop yield estimation, weed prediction, greenhouse gas emission forecasting, pest control, climate prediction, and crop risk assessment (Zhao et al., 2023). More specifically, AI can contribute to improving crop yields by accurately predicting optimal planting and harvesting periods, monitoring crop health, and reducing agricultural input costs such as chemicals, fertilizers, and irrigation (Hamrani et al., 2020). Consequently, AI helps minimize agricultural risks by addressing issues such as precipitation scarcity, weed proliferation, and losses due to disasters (Zhao et al., 2023).

Deep Learning (DL) and Machine Learning (ML) are two subfields of AI (Wang et al., 2023a). With ML, computers learn autonomously to improve AI performance by performing explicit feature extraction. ML emphasizes the performance, theory, and properties of learning systems and algorithms, positioning itself as a cutting-edge computer technology for quantifying and comprehending data-intensive agricultural processes. Conversely, DL can address problems using combinations of layers and nonlinear functions (Shin et al., 2022). To overcome the challenges of implementing mobile terminals, robots, and smart devices in modern agriculture, the integration of machine learning algorithms has made substantial advancements. Machine learning models have enabled innovative and more precise detection methods, addressing limitations such as constrained computing power, limited storage capacity, environmental complexities, and precision issues associated with detecting small targets (Wang et al., 2023a). Moreover, machine learning techniques can decrease the necessity for extensive networks and enhance the operational speeds of these systems (Wang et al., 2023a). These advancements have widespread applications, including precise detection of fruits and pests, as well as optimization and prediction of intricate conditions in plant tissue cultures and selection processes (Punithavathi et al., 2023).

Blockchain is a decentralized and distributed technology that maintains a growing ledger of ordered records or blocks, initially used in the context of cryptocurrencies (Sendros et al., 2022). It offers features such as transparency, immutability, and data reliability, thereby enhancing trust among different parties in the supply chain (Sendros et al., 2022). This technology, by eliminating operational hurdles, is now finding applications in the agricultural sector, facilitating the integration of digital technologies. For instance, the “IoT-Applied Greenhouse Monitoring System” uses blockchain to provide remote control of agricultural equipment (Sendros et al., 2022). Although blockchain is still in development, it promises a reliable, fast, and secure platform for monitoring agricultural operations (Liu et al., 2020). By enabling secure communication in a distributed network, it can help improve the planning of agricultural processes, particularly in the food supply chain. This is particularly crucial for addressing food security issues and challenges related to fragmented information in the supply chain (Sendros et al., 2022).

13.7 Water Management Strategies

Water is crucial for long-term agricultural growth, and increasing water use efficiency remains a significant challenge. Pressure on water availability for agriculture is increasing due to global warming and growing non-agricultural demand. Comprehending the interplay between plant water utilization, weather conditions, plant physiology, and soil properties is crucial for optimizing irrigation efficiency (Chen et al., 2023a). Drip irrigation is a promising solution, saving up to 27% of water without compromising yield (Wang et al., 2023b). However, it requires adaptation to farm size, installation costs, layout, and maintenance. Other traditional approaches, such as deficit irrigation, have been used to save water, but their impact on yield depends on water consumption (Wang et al., 2023b). Exploring innovative techniques is crucial for efficient water management without seriously compromising crop yield.

13.7.1 Innovative Techniques

13.7.1.1 Automation in Micro-irrigation

Using automatic systems to monitor soil moisture allows for precise irrigation of plants. The application of sensors in agriculture makes it possible to determine the actual moisture content in diverse parts of the plot and the needs of plants at different growth stages. Thus, irrigation is carried out directly at the place of interest, thus eliminating any generalization. As per Domínguez-Niño et al. (2020), sensor-based automated drip irrigation systems deliver the precise amount of water directly to plant roots. This approach minimizes water wastage, conserves resources, and

provides precise and efficient water management. By addressing water and labor limitations, this technique balances reduced water consumption with an overall improvement in agricultural productivity (Pugel et al., 2022).

13.7.1.2 Smart Irrigation

An intelligent Internet of Things (IoT)-based remote monitoring and control system for irrigation, employing diverse sensors and actuators, showcases the prospect of streamlined and automated irrigation management. The primary goal of this system was to improve agricultural productivity by enabling remote autonomous monitoring and operation (Roopaei et al., 2017). Using IoT technology, farmers can monitor soil moisture in real-time via a mobile app or web page, obtaining accurate information on the status of sprinklers. The system relies on real-time data on the water status of the soil captured by sensors to precisely provide the quantity of water needed. This innovative approach reduces manual efforts spent in the irrigation process, leading to significant improvement in agricultural efficiency and production (Roopaei et al., 2017).

Recently, innovative approaches have been introduced for intelligent irrigation systems, using various computational techniques, to ensure efficient water management in crops to increase yield and reduce irrigation loads by enhancing water use efficiency (WUE) (Domínguez-Niño et al., 2020). Smart irrigation based on AI can mimic adaptive decision-making (Adeyemi et al., 2018). Control systems, such as those based on artificial neural networks (ANN) (Ahmed et al., 2023) and expert systems (Janjanam et al., 2021), can be used to accurately determine the amount of water necessary for crops taking into account weather and soil conditions. Hybrid intelligence systems, combining AI algorithms such as fuzzy logic and neural networks, have been applied to irrigation control (Adeyemi et al., 2018). Deep learning, developed to solve long-term problems faced by AI, finds applications in agriculture due to its advanced hierarchical structure (Kia et al., 2009). A predictive control system can be used to model the movement of water in channels, maintaining a specific water level at various points and regulating the flow of water affecting those water levels (Adeyemi et al., 2018). Alternative approaches include variable rate irrigation (VRI), which applies irrigation at variable rates to different areas of the field in an optimized, precise, and rapid manner, based on spatiotemporal soil characteristics and plant demand (Serrano et al., 2020). While implementing variable irrigation management can improve the economic value of irrigation by boosting WUE, and productivity, and decreasing nutrient leaching (Liang et al., 2016), its use is limited due to higher costs, and the complexity of developing soil maps and maintaining the system. Furthermore, recent studies have focused on the use of drones for irrigation forecasting and monitoring, using infrared or thermal cameras in the IoT network (Bauer & Aschenbruck, 2018). Multi-band images captured by drones equipped with Internet of Things (IoT)-based sensor networks have been employed in precise and intelligent irrigation, leading to a significant enhancement in crop productivity (Boursianis et al., 2022). Other studies have investigated the

Table 13.3 Examples of innovative techniques in irrigation for water use efficiency

Approaches	Examples	References
Sensors	Using capacitive soil moisture sensors (FDR) in growing beans, wheat, and tomatoes saved up to 44% in irrigation energy	Conesa et al. (2021), El-Naggar et al. (2020), O'Shaughnessy et al. (2020)
	Based on data from the mission's satellites, the adjusted crop coefficient (Kc-VI) was used to calculate wheat evapotranspiration	French et al. (2020)
Drones	The use of hyperspectral images captured by drones has been exploited to assess the water deficit status of tomato plants and citrus crops	Bellvert et al. (2016), Susič et al. (2018)
	The employment of hyperspectral drone technology, combined with machine learning techniques, has been reported to differentiate between water-stressed and non-water-stressed vines	Loggenberg et al. (2018)
Artificial intelligence	The water status of plants was determined by artificial neural networks (ANN). Using this technique, energy and water savings of up to 20.5% were noted in a strawberry orchard	Adeyemi et al. (2018), Gu et al. (2021), Romero et al. (2018), Shaikh et al. (2022)
	The use of pulse-coupled networks (PCN) to assess soil water status and crop growth has been reported	Bachour et al. (2015)
	The combination of multi-resolution wavelet analysis with the MVRVM (multivariate relevance vector machine) algorithm was used to predict evapotranspiration (ET ₀) over 16 days	Kamilaris and Prenafeta-Boldú (2018)
	Deep learning (DL) has been reported as a machine learning technique that has shown good positive results for estimating weekly crop evapotranspiration	Patil and Deka (2016)
	The use of the AQUACROP model integrated with a dynamic neural network simulated soil humidity for a cotton crop	Li et al. (2019)
	A fuzzy irrigation system was used to quickly and accurately calculate evapotranspiration (ET ₀)	Mousa et al. (2014)
	Numerous researchers have employed expert systems in irrigation management, where these systems leverage diverse knowledge-based inputs to make precise decisions in irrigation planning	Eid and Abdrabbo (2018), Ragab et al. (2018)
	A hybrid machine learning system, incorporating fuzzy PID and GAPSO, was applied to evaluate soil moisture conditions. The outcomes indicated a notable 52% decrease in consumption	Mehra et al. (2018), Perea et al. (2019), Tsang and Jim (2016)
	Several researchers have used the model predictive control (MPC) technique to regulate canal irrigation flow rates	Abioye et al. (2023), Bwambale et al. (2023), Zhang et al. (2015)
	Studies have shown that corn, soybean, and wheat crop productivity was significantly better with VRI irrigation than with uniform flow irrigation	Sui and Yan (2017), Zhao et al. (2017)
	The use of capacitive soil moisture sensors (like FDR) in bean and sorghum cultivation has resulted in savings between 27% and 44%	Chen et al. (2022), Gu et al. (2020)
	By combining weather data and those captured by sensors, irrigation was controlled for tomato and wheat crops	Chen et al. (2019)

use of IoT-based mobile applications for smartphones to effectively manage crop irrigation (Liang et al., 2016). A decision support system (DSS) is a communicating software capable of identifying, analyzing and making decisions based on raw data to predict future irrigation needs (Gu et al., 2020). Various DSS have been developed to manage irrigation water to improve crop water use efficiency (Bauer & Aschenbruck, 2018). In order to achieve smart and efficient status, a DSS must integrate several factors, including soil moisture status, crop type, irrigation technique, weather data, and application parameters.

13.7.2 Regional Applications and Impact on Crops

The use of innovative techniques in crop irrigation is of crucial importance in the context of modern agriculture. These technological advances make it possible to optimize the use of water resources, ensuring precise and efficient distribution of water to plants. Techniques such as soil moisture sensors, automated systems, and smart irrigation contribute to more precise water management, thereby promoting environmental sustainability. By reducing water loss and avoiding over-irrigation, these innovative methods not only conserve precious water resources but also help increase crop yields. Additionally, the application of advanced technologies in irrigation provides farmers with the opportunity to make informed decisions based on real-time data, thereby improving productivity, profitability, and resilience to climate challenges. In Table 13.3, concrete examples are presented illustrating the application of innovative techniques in the irrigation of various crops.

13.8 Digital Agriculture and AI Applications

13.8.1 The Agricultural Revolution: Unleashing the Power and Importance of Artificial Intelligence

The integration of AI into the agricultural sector signifies a pivotal development, ushering in transformative changes in our approach to food production and crop management (Malhotra & Khan, 2022). This technological evolution not only brings about substantial benefits but also serves as a catalyst for optimizing farming operations, enhancing yields, and ensuring a judicious use of resources (Jha et al., 2019).

Employing sophisticated algorithms, AI plays a pivotal role in maximizing agricultural yields by discerning intricate patterns within data (Malhotra & Khan, 2022). This capacity facilitates precise resource management, improved crop planning, and reduced losses, thereby contributing to a more streamlined and efficient food production process (Balakrishna et al., 2021). AI's adept understanding of the specific

needs of individual plots of land enables the meticulous management of inputs such as fertilizers, water, and pesticides. This targeted approach ensures that crops receive precisely what they require, minimizing waste and optimizing resource utilization (Malhotra & Khan, 2022). Utilizing predictive models, AI assists farmers in strategically planning crop rotations and planting periods, optimizing land usage and minimizing periods of inactivity, ultimately contributing to higher annual yields. Additionally, AI's rapid detection capabilities allow for the swift identification of potential pests and diseases, enabling prompt and accurate intervention and mitigating crop losses due to biotic factors (Balakrishna et al., 2021). Given the significant effect of climate change on crops, real-time monitoring of weather conditions, water availability, soil quality, and specific crop needs by AI enables farmers to adapt swiftly and effectively to climatic variations, thereby minimizing risks to yields. Furthermore, AI systems exhibit a continuous learning capability, assimilating insights from data collected over time. This ongoing learning process results in increasingly accurate recommendations and decisions throughout agricultural seasons, contributing to a sustained enhancement in yields (Malhotra & Khan, 2022).

Artificial intelligence plays a pivotal role in revolutionizing agriculture through the automation of various tasks, spanning from the planting phase to the harvesting process. This automated approach not only yields substantial benefits for farmers but also significantly enhances the overall efficiency of farming operations. Primarily, AI-powered automation translates into considerable time savings for farmers (Kim et al., 2019). Through the optimization of processes such as planting planning, crop management, and harvesting, farmers can reduce the time spent on manual and repetitive tasks, enabling a greater focus on strategic decision-making activities (García et al., 2020). Furthermore, agricultural automation, bolstered by AI, brings about a marked improvement in operational efficiency. Autonomous robots, guided by sophisticated AI algorithms, exhibit a heightened level of precision when executing specific tasks. For instance, sensor-equipped robots can adeptly navigate through fields, identify weeds, and selectively eliminate them, thereby diminishing the necessity for excessive pesticide use (Pathan et al., 2020). The application of autonomous robots in the harvesting phase is also a critical domain. Automated machines can be programmed to undertake intricate tasks such as selectively picking fruits or harvesting crops at optimal moments (García et al., 2020). This not only expedites the harvesting process but also minimizes waste by ensuring a precise and efficient collection of crops (Kim et al., 2019).

Genetic innovation in agriculture, empowered by AI, marks a significant leap forward in the research and development of robust crop varieties tailored to evolving environmental conditions (Gupta et al., 2022; Pathan et al., 2020). This pioneering approach relies on a thorough analysis of crop genetic data, providing scientists and farmers with the insights needed to make informed decisions that enhance food security (Whelan et al., 2020). Leveraging AI for genetic data analysis enables researchers to pinpoint genetic markers associated with specific traits, including disease resistance, tolerance to extreme weather conditions, and enhanced productivity. This wealth of genetic information guides the selection and crossing of plants, expediting the traditional crop improvement process (Serraj & Pingali, 2019). One

key advantage of this approach lies in its capacity to cultivate crop varieties better suited to dynamic environmental changes, encompassing climatic variations and biotic pressures. For instance, the identification of genes linked to disease resistance empowers scientists to engineer crop varieties with heightened resilience, consequently reducing reliance on pesticides (Whelan et al., 2020).

In conclusion, AI is emerging as a pivotal catalyst in the agricultural transformation, presenting innovative solutions to address contemporary challenges and ensure sustainable food production in the future. Its gradual integration sets the stage for a more intelligent, efficient, and resilient agricultural sector.

13.8.2 Crop Yield Optimization Through Artificial Intelligence

Concrete examples derived from case studies vividly illustrate the tangible and positive impact of deploying innovative technologies to enhance efficiency in agricultural practices. Below, we delve into several particularly enlightening scenarios:

In a study comparing six AI models, the deep neural network (RNP) model underwent an optimization process to determine the best configurations for optimizer, layer structure, activation function, cost function, and dropout ratio. Using a July–August (JA) database, this model demonstrated a striking 17–22% and 21–33% improvement in accuracy for predicting soybean and maize yields, respectively, compared to the other models. The findings suggest that, with the JA database, soybean and maize yields for a given year can be predicted in early September, over a month before the harvest (Kim et al., 2019). Another study compared various modules, including the spray programmer, zone spraying, buffer zones, and product recommendation. This comprehensive approach ensures that crop protection products are applied precisely when and where needed, minimizing environmental impact while enhancing farmer productivity and profitability. Real-life case studies in Europe and Brazil demonstrated substantial reductions in fungicide use (30% in Europe) and herbicide consumption (61% in Brazil), resulting in decreased environmental pollution (Kim et al., 2019). IoT sensors deployed in fields across regions with significant climatic variations monitor real-time data on weather conditions, soil moisture, and other parameters. AI algorithms process this information, considering the specific needs of each crop and changing environmental conditions. This approach fine-tunes irrigation schedules, leading to a substantial decrease in water consumption, cost savings, and a substantial increase in crop yields. AI-assisted genetic selection studies have expedited the development of highly resistant crop varieties (Mesías-Ruiz et al., 2023). By reducing the time traditionally required for selection, this approach has enhanced yield stability and contributed to the cultivation of crops better suited to changing environmental conditions (Mesías-Ruiz et al., 2023).

In summary, these case studies showcase how the strategic application of AI and cutting-edge technologies can significantly optimize crop yields, offering both economic and environmental benefits. Such approaches are crucial in addressing the mounting challenges of agricultural sustainability and food security.

13.9 Challenges and Future Prospects

13.9.1 Hurdles and Challenges: Unpacking Obstacles to Technology Adoption

The integration of cutting-edge technologies, such as precision farming and AI, holds substantial promise for modern agriculture. However, the widespread adoption of these innovations encounters several hurdles. In certain regions, particularly in developing countries, farmers may confront limited access to essential resources necessary for the implementation of new technologies (Dagnaw, 2020). Challenges include a lack of access to electricity, unreliable internet connectivity, and insufficient specialized training. The significant upfront investment required to acquire and implement advanced technologies can be particularly prohibitive for farmers on small-scale operations, constraining their ability to embrace these transformative tools (Dagnaw, 2020). The effective utilization of technologies like AI demands specialized skills, making appropriate training a critical factor. The absence of proper training emerges as a major impediment to technology adoption, as farmers need to comprehend and adeptly employ these tools. Moreover, deeply ingrained traditional farming methods within the cultural and routine practices of farmers present a formidable barrier. The adoption of new technologies necessitates a substantial shift in daily practices, a transition that can be challenging for some to embrace (Dwivedi et al., 2021). The complexity of certain systems, notably in the realm of AI, may induce reluctance among farmers. The perception that these technologies are intricate and demanding to understand and implement on a daily basis may hinder their acceptance. Additionally, the rapid evolution of technologies raises concerns among farmers about the potential swift obsolescence of their investments. Fear of investing in solutions that may become outdated within a short period can deter adoption (Dagnaw, 2020).

To surmount these obstacles, collaborative efforts from governments, technology companies, and farming organizations are imperative. This collective initiative involves providing comprehensive training programs, developing essential infrastructure, reducing financial barriers, and formulating regulatory policies conducive to the seamless integration of new agricultural technologies.

13.9.2 Innovations, Sustainability, and Collaborative Pathways for a Resilient Future

The future of agriculture hinges on a strategic amalgamation of innovative technologies, sustainable practices, and collaborative engagement among diverse stakeholders. The envisioned directions for research and application aim to forge a more resilient, efficient, and environmentally friendly agricultural sector, poised to address the escalating demands of the global population.

Within the realm of agriculture, crop protection and optimization emerge as indispensable facets, involving safeguarding crops from various threats, including weeds, diseases, and pests. Traditional methods, relying on herbicides, insecticides, and fungicides, often pose adverse effects on both the environment and human health. The transformative influence of robotics and AI introduces novel tools for enhancing crop protection and augmenting yields (Mesías-Ruiz et al., 2023). Robotic and AI-based crop protection solutions leverage sensors, cameras, and machine learning algorithms to meticulously monitor crops and identify potential threats. These innovative solutions present distinct advantages over conventional methods, encompassing heightened precision, efficiency, and profitability (Pathan et al., 2020). For instance, robots equipped with sensors can pinpoint pest infestations and apply targeted treatments precisely where needed, minimizing chemical usage and reducing environmental impact. Furthermore, AI algorithms, drawing insights from extensive data on weather patterns, crop growth, and soil conditions, facilitate the prediction of potential risks and suggest preventive measures. This informed decision-making empowers farmers to identify issues effectively, select the most suitable pesticides and application technologies, and implement reduced-risk crop protection (Pathan et al., 2020).

13.10 Conclusions

The continuous expansion of the world's population places significant pressure on agriculture to ensure global food and nutritional security. This challenge is further intensified by the escalating concerns of climate change, alarming the entire world. Key climate factors, including precipitation, temperature, and greenhouse gases, have substantially impeded irrigation resources, heightened pest infestations, affected soil fertility, and influenced plant physiology and development. Several reports underscore the devastating impacts of climate change on plant growth and yield, predicting a significant decline in agricultural production in the coming years. Changes in precipitation patterns and fluctuations in temperature are highly significant indicators of environmental stress. Overcoming the effect of climate change on agricultural production proves to be a formidable challenge. The resolution of this issue and the adoption of effective strategies remain uncertain. Therefore, there is a need to emphasize agricultural technologies, strategies, and practices that optimize the growth and development of plants in the presence of biotic and abiotic stresses. These measures include the adoption of agricultural practices that optimize plant growth and mitigate the harmful effects of abiotic stresses. Smart water and nutrient management practices play a central role in this optimization. Additionally, applying knowledge in biotechnology and genetic engineering offers the possibility of designing new climate-resistant varieties. Furthermore, advances in nanotechnology and climate-smart agriculture present significant opportunities to further mitigate the effects of climate change on agricultural production. It is essential to

coordinate these approaches as part of a comprehensive and interconnected global strategy, contributing to the establishment of a sustainable and equitable food security system.

Acknowledgments This research received financial support from the Phytopathology Unit within the Department of Plant Protection and Environment at The Ecole Nationale d'Agriculture de Meknès.

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Chapter 14

Intervention of Hydroponics and Aeroponics for Climate-Resilient Cultivation



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14.1 Introduction

In an era of rapid climate change and escalating environmental degradation, the need for agricultural adaptation to ensure food security and sustainability has never been greater. Traditional soil-based farming, once the foundation of global food production, is now facing numerous challenges, including unpredictable weather patterns, rampant soil erosion, dwindling water resources, and a never-ending onslaught of pest infestations. Falcon et al. (2022) predicted that global food demand would increase by nearly 50–60% between 2019 and 2050. In the face of these mounting pressures, innovative solutions are critical to protecting our agricultural systems and ensuring food security. Two innovative farming technologies, hydroponics, and aeroponics, have emerged with the potential to revolutionize contemporary farming. Both methods present promising opportunities for crops to grow in a climate-resilient manner, without the limitations of conventional soil-based agriculture.

Hydroponics may be defined as plant growing process in soilless media using a nutrient-rich solution containing phosphates, nitrates, ammonia, and other macro- and micro-nutrients. Plant roots use clay pebbles as a growth substrate to aid in the absorption and transportation of the solution. Aeroponics is similar to soilless agriculture but without the use of clay pebbles. The roots are left hanging and are regularly supplied with a fertilizer solution (Raviv et al., 2008). The soilless nature of

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hydroponics and aeroponics is central to their appeal, as it allows for meticulous management of water and nutrient resources while also significantly reducing reliance on arable land. This makes them ideal for use in urban areas where land scarcity is a major concern. Aeroponics is very useful in dry areas with little water and poor soil quality. These techniques also promise to drastically cut down on the usage of chemical pesticides and herbicides, which will yield cleaner product and have a less negative environmental effect. This chapter embarks on an exploration of the intricate mechanisms, manifold benefits, formidable challenges, and diverse applications of hydroponic and aeroponic systems. By delving into the inner workings of these innovative technologies, we seek to lay the groundwork for their wider adoption and integration into mainstream agriculture. By utilizing the power of technology and innovation, hydroponics and aeroponics hold the potential to catalyze a paradigm shift in agricultural practices, ushering in a future characterized by resilience, sustainability, and abundance.

14.1.1 Historical Context and Evolution

While often perceived as cutting-edge technologies, hydroponics and aeroponics have ancient roots. Soilless cultivation can be traced back to early civilizations that employed various techniques to grow plants without traditional soil. The Hanging Gardens of Babylon, which falls within the Seven Wonders of the Ancient World, is one of the earliest examples of this method (Halley, 1965). Historians suggest that the lush greenery, perched atop terraces, was possible due to a form of early hydroponics that utilized a circuitous irrigation system to deliver water and nutrients. Similarly, the floating gardens of the Aztecs, or Chinampas, showcased an ingenious form of water-based agriculture (Resh, 2012). These agricultural platforms were built on shallow lake beds and relied on nutrient-rich water for plant growth. John Woodward, a seventeenth-century scientist, is credited with pioneering the use of hydroponics for growing plants in water culture (Hershey, 1994). First popularized in the early 1900s, modern hydroponics was primarily made possible by Dr. William Frederick Gericke of the University of California. He coined the term “hydroponics” and demonstrated its potential through a series of experiments and public demonstrations (Resh, 2012). Gericke’s work laid the foundation for contemporary hydroponic systems that now support commercial agriculture worldwide. In contrast, aeroponics is a more recent development, emerging in the 1980s. Driven by the space race and NASA’s interest in sustainable food production for long-duration space missions, scientists sought methods that could provide high yields with minimal resource inputs. Aeroponics, where plants grow with their roots are suspending in the air and are periodically misted with nutrient solutions, offers an efficient and space-saving solution. NASA’s pioneering work validated aeroponics as a viable agricultural technique, leading to its adoption in both terrestrial and extraterrestrial applications.

14.1.2 Principles of Plant Growth

The principles of plant growth in hydroponic and aeroponic systems are guided by the need to deliver water, nutrients, and oxygen efficiently. These methods aim to replicate—and improve upon—the ideal growing conditions found in soil-based agriculture.

Nutrient Delivery

In both hydroponics and aeroponics, plants are given a nutrient solution specifically formulated to meet their needs. In hydroponics, this solution is dissolved in water and delivered directly to plant roots. The precise composition of the nutrient solution can be adjusted based on the plant species and growth stage, ensuring optimal nutrition. Aeroponics takes this a step further by delivering nutrients through a fine mist. High-pressure spray nozzles distribute the nutrient solution as a mist, which enables direct uptake by plant roots. This method ensures that plants receive the necessary nutrients without any medium acting as a buffer, allowing for more immediate absorption and less waste.

Oxygenation

Optimal oxygen levels are crucial for plant root health. In traditional soil cultivation, overwatering can lead to anaerobic conditions, where roots are deprived of oxygen, causing root rot and other maladies. Hydroponic and aeroponic systems, however, are designed to maximize oxygen availability. In hydroponics, techniques such as air stones and continuous water flow are used to keep the nutrient solution oxygenated. Aeroponics naturally excels in oxygen delivery, as the roots are freely hanging in the air with periodic misting, which ensures they remain well-oxygenated. This environment enhances root respiration and nutrient uptake efficiency.

Water Efficiency

One of the most significant advantages of hydroponics and aeroponics is their water efficiency. Traditional agriculture is notoriously water-intensive, with much of the water used being lost to evaporation, runoff, and seepage. Hydroponic systems use closed-loop systems where water is recirculated, minimizing waste. Aeroponics uses even less water, as the misting process ensures plants receive only what they need, with excess moisture dripping back into the system for reuse. Both techniques use a lot less water than soil-based agriculture, which makes them perfect for areas where water is scarce.

14.2 Controlled Environment Agriculture (CEA)

Hydroponic and aeroponic systems are often integrated into Controlled Environment Agriculture (CEA) setups, where environmental conditions such as temperature, humidity, light, and CO₂ levels can be closely monitored and adjusted. Operating indoors or in greenhouses, these systems offer a stable environment that is shielded

from the vagaries of external climate conditions, including extreme weather events. With climate change leading to increased frequencies of droughts, floods, heat waves, and cold snaps, traditional farming faces significant risks. However, CEA can mitigate these risks by providing a consistent growing environment. Even in harsh external weather conditions, crops can thrive, ensuring a reliable food supply.

In addition to climate control, CEA allows for effective pest management. The enclosed environments of hydroponic and aeroponic systems significantly reduce the exposure of plants to pests and diseases. This is particularly important given the increasing resistance of pests to chemical pesticides and the rising concern over pesticide residues in food. These systems lessen the need for chemical treatments, which can have negative effects on the environment and public health, by reducing insect infestations. These farming systems' resistance to pests can be further increased by implementing integrated pest management techniques, which also include the use of physical barriers and biological control agents.

14.2.1 Hydroponic Systems

Hydroponics offers a controlled environment for cultivating plants without traditional soil. This allows for efficient resource utilization and optimized growing conditions, making it a valuable tool for climate-resilient agriculture. Here, we explore three prominent hydroponic system designs:

Deep Water Culture (DWC)

DWC systems provide a simple yet effective approach. Plants are suspended in a reservoir containing a continuously aerated nutrient solution. By ensuring the best possible oxygen availability for root respiration, this encourages quick development of the plant. To ensure the best possible plant health, DWC systems need to have their nutrient levels and pH closely monitored. DWC systems are also well-known for being appropriate for growing big plants with deep root systems. Because DWC systems continuously supply nutrients and water directly to the roots, they are especially well-suited for big plants with vast root systems. This method also supports the cultivation of various leafy greens and herbs, showing significant improvements in growth and nutrient uptake (Gillespie et al., 2020, 2021). DWC systems provide a continuous supply of oxygen to the plant roots through the use of air pumps. This constant aeration promotes healthy root growth and prevents root rot, a common issue in other hydroponic systems without continuous oxygenation (Sharma et al., 2019). The large volume of water in DWC systems provides a stable environment for nutrient uptake. This stability helps maintain consistent pH and nutrient levels, reducing the need for frequent adjustments and monitoring compared to NFT and Ebb and Flow systems (Rahmawati et al., 2021).

DWC systems have a straightforward design with fewer moving parts, making them easier to set up and maintain. This simplicity can be beneficial for beginners and those looking to reduce the complexity of their hydroponic setups (Morgan,

2021). On the other hand, DWC systems require continuous aeration which increases energy consumption and operational costs compared to passive systems like ebb and flow (Nursyahid et al., 2021). Also, the systems demand high-quality water free from contaminants. Poor water quality can lead to the accumulation of harmful substances in the nutrient solution, impacting plant health and yield (Aires et al., 2023).

Nutrient Film Technique (NFT)

Effective oxygenation and nutrition supply are given top priority in NFT systems. Plants in a shallow trough have a thin layer of fertilizer solution constantly recirculated over their exposed root zone (Fig. 14.1). This constant flow ensures continuous nutrient uptake and gas exchange, maximizing plant growth potential. NFT systems are particularly well-suited for cultivating leafy greens and herbs due to their efficient resource utilization and the ability to support high plant densities. NFT systems provide a continuous flow of nutrient solution, which ensures efficient nutrient uptake and oxygenation. The use of a thin film allows roots to access both nutrients and oxygen effectively, promoting healthy growth (Iswanto et al., 2020; Puerta et al., 2007). The continuous nutrient solution circulation ensures that plants get a steady supply of nutrients and oxygen. This promotes optimal growth conditions and helps avoid nutrient deficiencies (Silberbush et al., 2005; Spensley et al., 1978). NFT systems are particularly well-suited for cultivating leafy greens and

Fig. 14.1 Basil crop grown in NFT system



herbs. Their efficient use of resources and the ability to support high plant densities make them ideal for these types of crops (Tabaglio et al., 2020). NFT systems are highly space-efficient and can be easily stacked vertically. This makes them ideal for urban farming and areas with limited space. The design allows for the growth of a large number of plants in a relatively small area (Sharma et al., 2019). NFT systems generally have fewer moving parts and simpler designs compared to ebb and flow systems, which can make them easier to maintain and less prone to mechanical failure (Qurrohman et al., 2021).

Ebb and Flow (Flood and Drain) System

Ebb and Flow systems offer a cyclical approach to nutrient delivery. The plant growth medium (often inert materials like rockwool) is periodically flooded with a nutrient solution, allowing for thorough root zone saturation. The solution then drains away, facilitating oxygen replenishment. This cycle optimizes nutrient uptake and aeration, making ebb and flow systems suitable for a wider variety of crops compared to DWC or NFT. Furthermore, ebb and flow systems are known for their versatility in accommodating various plant types and growth stages. The NFT system requires continuous water circulation, which means the pump must run continuously maintaining the flow of nutrient solution. This results in higher energy consumption for the pump operation (Endryanto & Khomariah, 2022). In contrast, the ebb and flow system operates on a cyclical basis, where the pump only runs during the flooding phase and remains off during the draining and rest phases. This intermittent operation significantly reduces the overall energy consumption of the system (Siswanto & Widoretno, 2017).

14.2.2 Aeroponic Systems

An innovative method of soilless cultivation is aeroponics. In this instance, plant roots are suspended in a mist or air and are regularly doused with a nutritional solution that is highly oxygenated (Fig. 14.2). This method offers several advantages, particularly for climate-resilient agriculture. It provides better oxygenation to plant roots, promoting healthier root systems and improving overall plant growth. This is achieved because the roots are suspended in air and are more exposed to oxygen (Li et al., 2018). Aeroponics uses significantly less water compared to hydroponics. Water is delivered as a mist, which reduces water consumption and makes aeroponics highly efficient in water-scarce regions (Lakhiar et al., 2020). Aeroponics systems require specialized equipment such as misting devices, air pumps, and monitoring systems, leading to higher initial setup costs compared to hydroponics (Vatcharadze, 2021). Aeroponics systems are technically complex and require more maintenance and monitoring. Any failure in the misting system can quickly lead to plant stress or death due to dehydration (Bolivar et al., 2022). Although water-efficient, aeroponics can be energy-intensive due to the need for continuous misting and monitoring systems, which can increase operational costs (AlShrouf, 2017).

Fig. 14.2 Roots hanging in aeroponic chamber



There are two main types of aeroponic systems, namely high-pressure and low-pressure aeroponic system.

High-Pressure Aeroponics

High-pressure aeroponic systems deliver nutrient solutions as fine mists, which increases the surface area of water droplets. This enhances the contact between nutrients and plant roots, leading to more efficient nutrient absorption. The fine mist created by high-pressure nozzles allows for better coverage and distribution of nutrients, which can optimize plant growth and health (Tunio et al., 2021). However, high-pressure systems require precise engineering and can be more energy-intensive compared to other aeroponic methods. Despite this, they are favored for their ability to deliver nutrients effectively to the roots, especially in commercial settings where maximizing yield and efficiency are paramount.

Low-Pressure Aeroponics

This method offers a more cost-effective alternative to high-pressure systems. Low-pressure spray heads deliver a coarser mist to the plant roots. While nutrient absorption efficiency may be slightly lower compared to high-pressure systems, low-pressure aeroponics remains a viable option for controlled environment agriculture due to its simplicity and lower energy consumption. Moreover, low-pressure systems are preferred for their ease of maintenance and reduced risk of clogging, making them suitable for small-scale applications and research settings.

14.3 Advantages of Hydroponics and Aeroponics in Climate-Resilient Cultivation

Environmental Sustainability

Modern agriculture depends heavily on the usage of water, especially in areas where water shortage is becoming an increasingly pressing issue. In contrast to conventional soil-based farming, hydroponic and aeroponic systems distinguish themselves by significantly lowering water use. These systems may save up to 90% of the water used on average. By limiting evaporation and runoff and recirculating fertilizer solutions, this efficiency is attained. Aeroponics suspends roots in the air and sprays them with nutrients on a regular basis, whereas hydroponics does this by directly immersing plant roots in a nutrient-rich solution.

These methods are particularly beneficial in arid and semi-arid regions, where water resources are limited. Traditional agriculture in these regions often competes for water with other essential needs, such as drinking water and sanitation. By adopting hydroponic and aeroponic systems, communities can prioritize water efficiency, enabling sustainable food production without depleting precious water reserves.

Another significant advantage of hydroponic and aeroponic systems is their efficient use of space. Unlike traditional agriculture, where large tracts of land are required, these systems can be implemented in vertical farming setups, utilizing multi-layered growing spaces. This makes it possible to grow more produce per square meter compared to flat, single-layered fields. Such vertical farming systems are particularly valuable in urban environments, where land is often scarce and expensive. Urban agriculture can transform rooftops, vacant lots, and even indoor spaces into productive farming areas, contributing to food security in cities. This reduced requirement for arable land also means that natural ecosystems are less likely to be disrupted or converted into farmland, preserving biodiversity and reducing habitat loss.

Consistent and Higher Yields

The ability of hydroponic and aeroponic systems to produce year-round is one of its most notable advantages. Traditional farming is often bound by seasonal cycles, with planting and harvest times being dictated by the local climate. However, in a controlled environment, plants can be cultivated continuously without regard to seasonality. This capability not only boosts overall productivity but also ensures a steady supply of fresh produce throughout the year. For consumers, this translates into access to a wider variety of fruits and vegetables regardless of the season, while for farmers, it means more predictable income streams.

You may optimize every element of the plant's growth environment with hydroponic and aeroponic systems. Plants obtain the precise minerals and elements they need for maximum growth because nutrient delivery is accurate and customized to meet the unique requirements of each crop. To produce the ideal growth environment, environmental variables like temperature, humidity, and light intensity and

duration may be carefully regulated in the interim. When compared to traditional farming, this degree of control frequently produces larger yields and quicker growth rates. Plants expend less energy on root development since they do not need to search for nutrients in the soil. Instead, they can focus more on growing foliage, flowers, and fruits.

Nutritional and Health Benefits

Emerging research suggests that soilless cultivation techniques can enhance the nutritional quality of produce. Because the nutrients in hydroponic and aeroponic systems are delivered directly to the roots in an easily accessible form, plants are often more nutrient-dense. For instance, leafy greens grown hydroponically have been discovered to possess greater concentrations of certain vitamins and antioxidants. In regions where soil quality is poor or contaminated, hydroponics and aeroponics can be particularly beneficial. Soil degradation and nutrient depletion are significant concerns for traditional agriculture, leading to less nutritious crops. Soilless systems bypass these issues, enabling the production of high-quality, nutrient-rich food.

Soilless cultivation also minimizes the risk of contamination from soil-borne pathogens and pollutants. Soil can harbor harmful microorganisms, heavy metals, and other contaminants that can be taken up by plants, posing risks to human health. Controlled environments for hydroponic and aeroponic systems maintain rigorous standards of cleanliness and hygiene, further reducing the risk of contamination. The absence of soil means fewer opportunities for pathogens to establish themselves, resulting in cleaner, safer produce. Additionally, because these systems often use less or no pesticides, the produce is generally lower in chemical residues.

14.3.1 Socioeconomic Impacts

Job Creation and Economic Development

The implementation of hydroponic and aeroponic systems can have significant socioeconomic benefits, particularly in regions with limited employment opportunities and economic diversification. These systems require skilled labor for operation, maintenance, and management, thereby creating employment opportunities in farming, technology, and related sectors. Additionally, the establishment of hydroponic and aeroponic farms can stimulate economic development by generating demand for locally sourced inputs such as construction materials, equipment, and agricultural supplies. Moreover, the production of high-value crops through soilless cultivation can enhance farm profitability and contribute to rural wealth creation, thereby reducing poverty and enhancing livelihoods.

Community Resilience and Food Security

Hydroponic and aeroponic systems contribute to community resilience by enhancing food security and reducing vulnerability to external shocks such as climate change, natural disasters, and market fluctuations. By enabling year-round

production of fresh produce in controlled environments, these systems ensure a consistent food supply regardless of seasonal variations or external conditions. This stability in food availability enhances food security for communities, particularly in remote or underserved areas where access to fresh and nutritious food may be limited. Moreover, the localization of food production through urban and peri-urban hydroponic and aeroponic farms reduces dependence on long-distance transportation and global supply chains, thereby enhancing food sovereignty and resilience to disruptions.

Empowerment of Small-Scale Farmers and Women

Hydroponic and aeroponic systems offer opportunities for small-scale farmers, including women and marginalized groups, to engage in profitable and sustainable agricultural enterprises. These techniques are more accessible to smallholder farmers with limited resources since they require less land and water than traditional agricultural methods. Moreover, the modular and scalable nature of hydroponic and aeroponic setups enables farmers to start small and gradually expand their operations as they gain experience and confidence. Additionally, the controlled environment and precise management techniques of soilless cultivation reduce the physical labor and drudgery associated with traditional farming, making it more attractive to women, who often bear the brunt of agricultural labor in many societies. By empowering small-scale farmers and women through access to modern agricultural technologies and market opportunities, hydroponics and aeroponics contribute to inclusive and equitable economic growth.

Education and Capacity Building

The adoption of hydroponic and aeroponic systems necessitates investment in education and capacity building to equip farmers, technicians, and stakeholders with the knowledge and skills required for successful implementation. Training programs, workshops, and extension services play a crucial role in disseminating best practices, technical know-how, and innovative techniques related to soilless cultivation. Furthermore, educational initiatives focused on STEM (Science, Technology, Engineering, and Mathematics) education can inspire the next generation of agricultural innovators and entrepreneurs to explore the potential of hydroponics and aeroponics. By investing in education and capacity building, governments, NGOs, and development agencies can foster a culture of innovation, entrepreneurship, and sustainability in agriculture, thereby driving long-term socioeconomic development and resilience.

14.4 Challenges and Solutions in Implementing Hydroponics and Aeroponics

Despite their numerous advantages, the widespread adoption of hydroponics and aeroponics faces certain impediments. This section explores these challenges and proposes potential solutions to facilitate the successful integration of these technologies into sustainable agricultural practices.

14.4.1 Technical and Financial Considerations

Establishing hydroponic or aeroponic systems requires a significant upfront investment in infrastructure. Specialized equipment includes grow lights for indoor vertical hydroponic cultivation, nutrient delivery systems, climate control units, and monitoring sensors. These costs can be substantial, particularly for large-scale operations. However, a long-term perspective is crucial. Hydroponics and aeroponics often lead to increased crop yields (up to 30% higher compared to soil), reduced water consumption (by 70% or more), and efficient land utilization (enabling vertical farming). Over time, these factors contribute to substantial operational cost savings, offsetting the initial investment. Additionally, advancements in automation and the development of modular systems can help reduce setup costs and improve scalability for smaller growers.

Successful operation of these systems necessitates a strong foundation in technical knowledge. Growers need to understand the intricacies of nutrient management, including formulation, monitoring nutrient solution pH and electrical conductivity (EC), and adjusting nutrient ratios based on plant growth stage and specific requirements. System monitoring encompasses tasks like maintaining optimal temperature, humidity, and CO₂ levels within the growing environment. Furthermore, growers need to be familiar with troubleshooting potential issues like pump malfunctions, clogged nozzles, and power outages. To address this challenge, educational programs and training initiatives can be implemented by universities, agricultural extension services, and private companies. These programs can equip growers with the necessary skills and knowledge through workshops, online courses, and certification programs. Additionally, the development of user-friendly automation systems with real-time monitoring and auto-correction capabilities can simplify operations for growers with less technical expertise. Readily available technical support from system manufacturers or hydroponic/aeroponic consultants can further facilitate technology adoption.

14.4.2 Integration with Established Agricultural Practices

Transitioning from traditional soil-based agriculture to hydroponics or aeroponics can be a significant shift for some growers. Unfamiliarity with the technology and potential skepticism about its effectiveness, particularly regarding crop quality and yield consistency, can lead to resistance to adopting these methods. Pilot projects showcasing successful real-world implementations can be highly beneficial. Demonstration farms established by universities, government agencies, or private companies can play a crucial role in driving adoption. These farms can allow growers to witness the technology firsthand, learn from experienced practitioners, and gain confidence in its capabilities. Additionally, hosting workshops and conferences focused on hydroponics and aeroponics can foster knowledge sharing and address grower concerns.

Governmental policies and regulations can significantly influence the integration of these novel technologies into mainstream agriculture. Currently, there may be a lack of clear guidelines and frameworks regarding hydroponics and aeroponics. Concerns related to food safety, water usage (particularly in drought-prone regions), and potential environmental impact (e.g., disposal of nutrient runoff) need to be addressed. Establishing clear regulations that ensure safe and sustainable practices can provide much-needed clarity and encourage wider adoption. Collaboration between government agencies, research institutions, and industry stakeholders is crucial for developing these frameworks. Additionally, financial incentives, such as tax breaks or subsidies, can further encourage growers to invest in these sustainable agricultural practices. By providing financial support, governments can acknowledge the environmental benefits of hydroponics and aeroponics and incentivize their adoption as a means to achieve broader sustainability goals.

14.4.3 Infrastructure and Resource Constraints

The successful implementation of hydroponics and aeroponics relies heavily on access to adequate infrastructure, including reliable electricity supply, water resources, and transportation networks. In regions with underdeveloped infrastructure, particularly in rural or remote areas, establishing and maintaining hydroponic or aeroponic systems can present significant challenges. Insufficient access to electricity may hinder the operation of climate control systems, while water scarcity could limit the availability of nutrient solutions for hydroponic cultivation. Furthermore, inadequate transportation infrastructure may impede the distribution of produce to markets, limiting the economic viability of such ventures. Addressing these infrastructure constraints requires coordinated efforts from governments, development agencies, and private sector stakeholders to invest in essential infrastructure development projects and improve access to basic services in underserved regions.

The efficient operation of hydroponic and aeroponic systems depends on the availability of essential resources such as nutrients, substrates, and energy inputs. While hydroponic systems utilize nutrient solutions as a substitute for soil, ensuring a consistent supply of quality nutrients can be challenging, particularly in regions with limited access to agricultural inputs. Similarly, aeroponic systems rely on a steady supply of water and electricity to maintain optimal growing conditions. In areas prone to water scarcity or energy shortages, securing these resources may pose significant obstacles to technology adoption. Developing sustainable supply chains for essential inputs and exploring alternative energy sources, such as solar or wind power, can help mitigate resource constraints and enhance the resilience of hydroponic and aeroponic operations. Moreover, promoting resource-efficient practices, such as water recycling and nutrient reuse, can reduce dependence on external inputs and promote long-term sustainability.

14.4.4 Market Dynamics and Consumer Perception

The adoption of hydroponics and aeroponics is influenced by market dynamics, including consumer demand, pricing trends, and competition from conventional agriculture. While there is growing interest in locally grown, sustainably produced food, consumer preferences, and purchasing behaviors can vary significantly across different markets. Furthermore, fluctuating commodity prices and unpredictable weather patterns can introduce uncertainty to the economic viability of hydroponic and aeroponic ventures. To navigate these market uncertainties, growers must conduct thorough market research, identify niche markets or value-added product offerings, and establish resilient business models that can adapt to changing market conditions.

Consumer perception plays a crucial role in shaping the market demand for hydroponically and aeroponically grown produce. While these technologies offer numerous benefits, including year-round availability, consistent quality, and reduced environmental impact, some consumers may have reservations or misconceptions about soilless cultivation methods. Addressing consumer concerns and building trust in the safety and sustainability of hydroponic and aeroponic produce requires transparent communication and education initiatives. Growers may communicate with customers by using certification programs, labeling, and educational efforts to clarify common misconceptions and emphasize the benefits of soilless agriculture. Moreover, building direct relationships with consumers through farmers' markets, community-supported agriculture (CSA) programs, or farm-to-table partnerships may increase consumer loyalty and confidence in hydroponic and aeroponic products.

14.5 Hydroponics in Urban Environments: Transforming Cityscapes into Food Oases

With cities throughout the world struggling to address issues of food security, environmental sustainability, and population expansion, urban agriculture is gaining popularity quickly.

Hydroponics, with its ability to produce high yields in limited spaces, is at the forefront of this urban agricultural revolution. Here, we delve into notable case studies showcasing the innovative use of hydroponics in transforming urban environments into thriving food oases.

Sky Greens in Singapore

Singapore, often heralded as a global leader in urban sustainability, is home to Sky Greens, the world's first commercial vertical farm. Founded in 2012, Sky Greens utilizes a patented A-Go-Gro system, which employs rotating tiers of hydroponic racks to maximize space and sunlight exposure. Located in a highly populated metropolitan area with little arable land, Sky Greens grows leafy greens for local consumption, including kale, spinach, and lettuce. By vertically stacking cultivation modules, Sky Greens optimizes land use efficiency, reducing the city-state's reliance on imported produce and minimizing its carbon footprint. Furthermore, the farm's proximity to urban centers ensures fresher, more nutritious produce for Singaporeans while bolstering food security in the face of global supply chain disruptions.

Farm. One in New York City

In the heart of bustling Manhattan, Farm. One has pioneered the use of hydroponics and aeroponics to cultivate gourmet herbs, edible flowers, and microgreens for some of the city's most renowned restaurants. Situated in a climate-controlled indoor environment, Farm. One utilizes vertical farming techniques to maximize space utilization and optimize growing conditions. Aeroponic systems deliver nutrient-rich mist to plant roots, fostering rapid growth and superior flavor profiles. By sourcing produce locally and sustainably, Farm. One reduces food miles and minimizes environmental impact, providing a more resilient and sustainable food system in one of the world's largest urban centers. Moreover, Farm. One offers educational tours and workshops, engaging the local community and fostering a deeper appreciation for urban agriculture and sustainable food production.

14.5.1 Aeroponics in Rural Development: Empowering Communities with Sustainable Agriculture Solutions

While hydroponics has garnered attention for its urban applications, aeroponics is emerging as a transformative technology for rural development, particularly in remote and underserved communities. Here, we explore innovative initiatives

harnessing the power of aeroponics to address food insecurity and promote economic empowerment in rural settings.

The Aerofarms Project in Rwanda

In Rwanda, where rugged terrain and limited arable land pose significant challenges to traditional agriculture, the Aerofarms Project is pioneering the adoption of aeroponics to bolster food security and economic resilience. Led by local entrepreneurs and supported by international NGOs, the project establishes community-run aeroponic farms in rural villages, providing training, technical assistance, and access to resources. These farms use aeroponic technology to grow a wide variety of nutrient-dense crops year-round, such as fruits, vegetables, and basic grains. This decentralized approach to agriculture empowers rural communities to become self-sufficient in food production while generating income through surplus crop sales. Moreover, the adoption of aeroponics promotes environmental sustainability by minimizing water usage and soil degradation, preserving fragile ecosystems for future generations.

The Greenhouses of Greenland

In the remote Arctic region of Greenland, where extreme cold and permafrost preclude traditional farming methods, aeroponics offers a ray of hope for food security and economic development. Here, innovative entrepreneurs have established greenhouse facilities equipped with aeroponic systems, enabling year-round cultivation of fresh produce in a harsh and unforgiving environment. Utilizing clean energy sources like wind and solar energy, these greenhouses operate sustainably, reducing reliance on imported food and fossil fuels. The adoption of aeroponics has not only improved access to nutritious food for local communities but also created employment opportunities and stimulated economic growth in remote regions. Furthermore, the success of these greenhouse projects serves as a model for sustainable development in other Arctic communities facing similar challenges.

14.6 Future Prospects

Hydroponics and aeroponics are on the cusp of a transformative era, driven by continuous advancements and a growing focus on expanding accessibility. This section delves deeper into the exciting possibilities on the horizon and explores initiatives aimed at making these technologies a cornerstone of sustainable agriculture.

AI and Machine Learning

Optimizing soilless farming may greatly benefit from the application of artificial intelligence (AI) and machine learning techniques. Large datasets on plant development, environmental factors, and nutritional requirements may be analyzed using these methods. By identifying patterns and predicting potential issues, AI can guide automated adjustments to environmental controls and nutrient delivery, maximizing yields and resource efficiency.

Precision Agriculture

The integration of advanced sensors, real-time data analysis, and automation promises to usher in an era of precision agriculture for hydroponics and aeroponics. Sensors can monitor not just environmental factors but also plant health parameters like chlorophyll content and leaf temperature. By customizing fertilizer supply and environmental conditions to each plant's unique requirements, this real-time data can help maximize growth and resource efficiency.

Robotics and Automation

Soon, soilless cultivation may involve increased automation through robotics. Robots can be programmed for tasks like transplanting seedlings, pruning plants, and crop harvesting. This will not only reduce labor costs but also minimizes human error, ensuring consistent and high-quality yields. Additionally, robots can be designed to operate in controlled environments more effectively than humans, further improving efficiency and optimizing resource utilization.

14.6.1 Expanding Accessibility

Open-Source Technologies

The open-source movement has the potential to democratize access to hydroponic and aeroponic technologies. By collaboratively developing and sharing low-cost, DIY system designs and readily available control software, the open-source community can empower individuals and small-scale farmers to implement these technologies without significant financial barriers.

Modular and Scalable Systems

Developing modular and scalable hydroponic and aeroponic systems can cater to diverse needs and budgets. Modular systems allow growers to start small and gradually expand their operations as their skills and resources grow. This flexibility can be particularly beneficial for small-scale farmers and urban agriculture initiatives.

Community-Supported Agriculture (CSA) Model

The CSA model, which connects consumers directly with local producers, can be a powerful tool for promoting hydroponics and aeroponics. By integrating soilless cultivation practices into CSAs, farmers can offer fresh, locally produced food year-round, even in regions with challenging climates. This not only benefits consumers but also creates a supportive ecosystem for the adoption of these sustainable agricultural methods.

14.6.2 Policy and Governance Frameworks

Regulatory Standards and Certification

Establishing robust regulatory standards and certification processes is essential for ensuring the safety, quality, and sustainability of hydroponic and aeroponic products. Governments and industry stakeholders must work together to develop transparent and enforceable guidelines that address key issues such as food safety, water management, and environmental stewardship. Certification programs can provide consumers with assurance that soilless cultivated produce meets rigorous standards, enhancing market confidence and driving adoption.

Incentive Mechanisms and Support Policies

At the municipal and national levels, policy incentives and support systems may be quite effective in fostering the use of hydroponics and aeroponics. The initial investment expenses of putting up soilless growing facilities might be partially offset by financial incentives like as grants, subsidies, and tax breaks. Additionally, research funding and technical assistance programs can support innovation and capacity-building efforts, facilitating technology transfer and knowledge exchange.

14.7 Conclusion

The potential of hydroponics and aeroponics to revolutionize modern agriculture extends far beyond their technical prowess. These transformative interventions offer a sustainable, efficient, and high-yielding approach to agriculture, empowering us to cultivate crops in a way that minimizes environmental impact and maximizes resource utilization. We can leverage the revolutionary power of soilless farming to build a more resilient, equitable, and sustainable agricultural future for future generations by embracing innovation, promoting cooperation, and placing a high value on inclusion. In the face of global food security challenges and climate change, hydroponics and aeroponics are shining examples of optimism. The scientific principles underpinning these technologies have been effectively demonstrated through successful case studies around the world. From vertical farms gracing the skylines of megacities to aeroponic systems nourishing remote communities, hydroponics and aeroponics are proving their adaptability and transformative potential.

The future of agriculture hinges on our ability to integrate these innovative practices into mainstream cultivation. Technological advancements like AI, automation, and precision agriculture promise to further optimize soilless cultivation, fostering even greater efficiency and resource conservation. Wider accessibility can also be ensured via projects centered on cost-cutting, the development of open-source technologies, and educational campaigns, especially for small-scale farmers and developing areas. We can pave the path for a more resilient, egalitarian, and sustainable agricultural future by fusing the holistic approach to sustainable food production symbolized by hydroponics and aeroponics with continued initiatives to promote

accessibility and innovation. A new age of climate-resilient agriculture may be ushered in by adopting hydroponics and aeroponics. These technologies offer a roadmap towards a sustainable future where food production is not dictated by the whims of weather patterns but guided by scientific precision and a deep respect for our planet's resources. As we navigate the unpredictable realities of climate change, hydroponics and aeroponics empower us to cultivate a more secure and abundant future for generations to come.

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Chapter 15

Innovative Techniques for Climate-Resilient Crop Production in Protected Environments



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15.1 Introduction

Climate change, in conjunction with a reduction in rural population, has diminished the effectiveness of conventional farming techniques. However, as the global population is projected to surpass 10 billion by 2050, with a substantial portion residing in urban areas, the demand for food is expected to continue to increase, especially in large cities (Hotez, 2017). The main aim of agricultural research has changed as a result of the growing global population and subsequent increase in food demand,

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as well as the negative effects of climate change on crop cultivation. Consequently, there is an increasing focus on growing crops in controlled environments to address these challenges (Choi et al., 2023). Protected cultivation has been used for decades globally, primarily for off-season crop production. This farming technique has gained immense popularity owing to its ability to controlled environmental conditions, resulting in improved plant performance, extended production periods, earlier yields, and higher quality (Gruda & Tanny, 2014). Greenhouses are widely employed for cultivating plants in protected environments using controlled environment agriculture (CEA), which incorporates a range of technical advancements. However, several strategies, such as vertical farming, rooftop gardens, and extensive indoor crop production, have been employed in this field (Concepcion et al., 2023). Implementing protected cultivation on its own presents difficulties due to variations in weather, soil quality, plant diseases, and other environmental factors. To achieve greater productivity, economic returns, and environmental sustainability, it is essential to utilize technologies that improve resource-usage efficiency and provide access to real-time data for predictive and sustainable production (Bationo et al., 2012). In addition, various technologies have been utilized in controlled environments to mitigate the effects of climate change and improve crop output and quality. These technologies concentrate on critical agricultural issues such as temperature regulation, water management, and fertilizer control (Choi et al., 2023). This chapter focuses on the primary consequences of climate change and global warming on agriculture and the environment while also evaluating the technological interventions implemented in protected settings to improve crop resilience to these changes, thus promoting agricultural productivity and quality.

15.2 Climate Change Trends and Impacts on Crop Production

Climate change has profoundly impacted global agricultural systems (Fig. 15.1), with forecasts predicting increased temperatures, altered precipitation patterns, and frequent extreme weather events (Pathak et al., 2018). Increasing levels of carbon

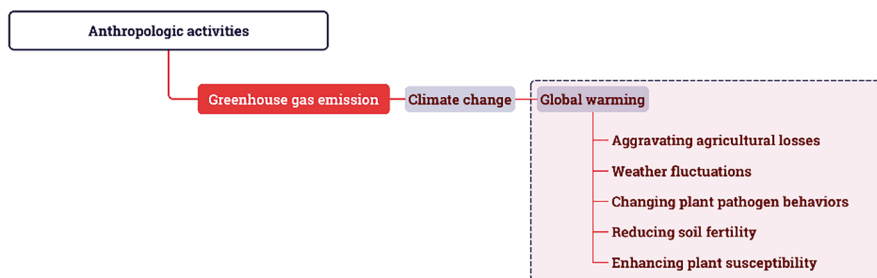


Fig. 15.1 Effects of anthropological activities on climate change and global warming and their adverse effect on environmental conditions and agricultural system

dioxide (CO₂) and other greenhouse gases are expected to negatively affect crop productivity and increase agricultural vulnerability. Key factors, such as temperature and water availability, which are essential for crop growth and productivity, are projected to be influenced by increased CO₂ and greenhouse gases (Altieri et al., 2015). This may also alter the behavior of pests, pathogens, and weeds. Drought and heat uniquely disrupt various aspects of plant growth compared to other stressors (Zandalinas et al., 2018). For example, high temperatures during flowering can reduce tomato fruit set by shortening the plant life cycle and inhibiting photosynthesis when temperatures exceed 30 °C (Fahad et al., 2017). Climate change can also decrease soil fertility owing to the excessive use of chemical fertilizers (Zhang et al., 2017a, 2017b). Hence, it is essential to devise innovative strategies to reduce the impact of climate change on agriculture and guarantee sustainable food security for the long term.

15.3 Protected Environment

Protected cultivation has been proposed to mitigate the effects of climate change on farms (Liao et al., 2020) and enhance farm sustainability (Liao et al., 2020). Morocco, Spain, Turkey, Brazil, China, Italy, Mexico, South Japan, and Korea have pioneered their adoption (Phani et al., 2021). CEA is becoming increasingly popular, especially in urban areas, to address climate change and food scarcity (Goodman & Minner, 2019). Facilities such as tunnels, net houses, and greenhouses are tailored to specific climates and plant varieties, offering benefits such as reduced weather-related crop loss, improved pest and disease resilience, efficient resource management, and higher crop yields and quality, leading to increased farmer incomes (Liao et al., 2020). Protected cultivation creates a controlled microclimate for plants (Harel et al., 2014), minimizes weather-related yield losses, enhances pest and disease resistance, and improves resource efficiency and crop quality (Liao et al., 2020). Advanced heating, cooling, and lighting systems in protected agriculture maintain favorable conditions, boost yields, and safeguard against adverse weather, diseases, and pests (Phani et al., 2021). This method enables year-round high-quality vegetable production, even on unproductive land with reduced agro-chemical dependence (Gruda et al., 2019).

Protected environments have certain limitations. Greenhouse cultivation in temperate regions demands significant energy for heating during colder months, which increases greenhouse gas (GHG) emissions. Greenhouse construction is influenced by factors such as snow accumulation, wind velocity, and hail, which require specialized engineering (von Elsner et al., 2000). Compared with open-field systems, greenhouses often have poorer air circulation, posing risks (Sammons et al., 2005). In hydroponic systems, plant transpiration and nutrient solution evaporation elevate humidity, which can enhance crop development and promote the spread of pathogens (Roberts et al., 2020). High tunnels are costly and yield fewer strawberries than open fields do (Mbarushimana et al., 2022). Addressing these challenges

necessitates the integration of advanced methods in protected environments to ensure effective pathogen control and enhance plant resilience to biotic and abiotic stressors.

15.4 Innovative Techniques for Climate-Resilient Crop Production in Protected Environments

15.4.1 Precision Agriculture

The increase in food demand due to surges in the human population has necessitated the inclusion of high-tech in agriculture. Precision agriculture aims to dispense error-free information regarding the properties of soil and crops for optimization of inputs, which is specifically tailored towards local needs. The use of fertilizers and pesticides is minimal, with a focus on their environmental benefits (Banu, 2015). Important variables that impact yield, such as meteorological, topographic, edaphic, anthropogenic, and biological factors, are factored into field management to eliminate unnecessary complications. The unprecedented negative effects of climate change and other severe environmental impacts on farm fields can be managed using information technology (Banu, 2015). Variability can be controlled to ensure optimum crop protection, profitability, and yield sustainability. Factors that limit productivity are automatically detected and corrected within the eye twinkle (Adamchuk et al., 2004). Soil is an important element in agriculture and can be distinctly monitored. Alterations in soil conditions, such as alkalinity, salinity, and acidity, which accumulate in nutrient deficiencies, toxicity issues, decrease in plant growth-promoting organisms, and reduction in water retention, have been managed through precision farming (Andrade-Sanchez et al., 2008). Soil sampling in conjunction with geographical coordinates has also been combined with quantize and types of fertilizers or other requisite actions necessary to mediate such occurrences in the soil (Andrade-Sanchez et al., 2008). Soil ion sensors have shown promising results. Accurate information about soil compaction spanning various depths in the soil is considered (Banu, 2015). Precision agriculture combines and understands natural field variability to realize increased efficiency. Inputs are administered specifically to sites to maximize long-term benefits. Some sensor technologies and automated systems in precision agriculture are highlighted below:

- **Process Monitoring Sensors.** A large number of sensors are provided to the harvesters by manufacturers. Calibrated yield systems include the idea of reducing the time spent. Forage harvesters are equipped with infrared spectroscopy sensors, such as moisture, starch, protein, and dry matter of grains during the harvesting process, and this information is needed to establish the use of fertilizer or manure on a specific farm site (Hague et al., 2000). Crop sensors with LED were built to evaluate nitrogen index and crop biomass.

- **Variable Rate Sensors.** This technology sustains the precise use of fertilizers, pesticides, and seed planting, with the aim of avoiding overlap. Primary tractor producers and agro-engineering organizations provide variable rate sensors as standards in tractor manufacturing, which often function with real-time sensors. In some cases, these functions rest on pre-loaded farm maps and tractor speed, and many variable sensors work with sprayers, seeders, and planters (Colaço & Bramley, 2018). Rate sensors are also manufactured with boom height and section managers to support uniformity in the spraying of fields; thus, the sensors calculate the distance to the crop canopy and ground. Problems such as blockages and equipment faults are also detected by sensors (Zagórda et al., 2017). Rate sensors are run by compatible terminals and task managers with the provisions of section and rate controls. Data were recorded on ISOXML files, which allowed the recording of future management decisions.
- **Machine Performance Sensors.** Recent developments in tractor automation have provided room for augmentation of various elements of tractor operations that are initially saddled with humans to optimize engine performance. Tractor gear selection has been improved to continuously variable transmission (CVTs) from the human mode (Howard et al., 2013). Thus, the power selection of the tractor depends on the variable load, speed, and revolutions per minute (RPM), which are adjusted automatically relative to the requirements. The efficiency of fuel use is equally controlled, whereas vehicle wear and tear is significantly reduced (Coffman et al., 2010). Sensors are also tailored to steering control. This is done to fine-tune operations, such as turning from the field to road movements, and the parameters for cleaning grains during harvesting are programmed with sensors. The sieve openings and fan speed were automatically programmed for adjustments to minimize losses and improve the grain quality. Sensors for slope descent and climbing were included by manufacturers (Majumdar & Jayas, 2000). The fan speed was censored and automated in the harvester for grain flow optimization to ensure clean grains. The optimization of inputs is based on sensor metrics. Images were used to determine the attributes of crops and field parameters such as plant vigor, canopy density, row spacing, plant height, and estimated yield. Automation of agricultural machines is prevalent. The avoidance of objects and laser range finders is part of recent improvements to reduce human operations to a minimum (Schueller, 2014).
- **Weeding Robots.** Robotic weeding has several benefits, such as high labor efficiency, reduction in energy consumption, work quality improvement, and efficient resource management (Peteinatos et al., 2014). The feeding robot operates with a 2D laser scanner for easy and accurate movement through field rows, thus saving time and energy for field workers (Reiser et al., 2019).
- **Tree Health Sensors.** Thermograms can also be used to evaluate tree deterioration. Diagnosis is made early enough for quick maintenance (Bellett-Travers & Morris, 2010). Thermograms were used to identify *Z. tritici* infection in wheat. Plant metabolism is influenced by fungal infections, and these are easily identified by thermograms prior to the appearance of physical symptoms (Wang et al., 2019). Crop yield predictions and nitrogen levels were measured using spectral

sensors. In some cases, complex algorithms, such as ambient sun radiation and the electrical conductivity of soil with aerial images, are pulled together for accurate yield prediction (Thorp et al., 2017).

15.4.2 Vertical Farming

The pressure on yield in agriculture owing to the excessive growth of the human population worldwide and the loss of arable/farmland to infrastructural developments has led to new food production techniques (Thomaier et al., 2015). The idea of vertical farming came up with an alienate reduction in yield associated with traditional farming techniques, and wild crop production per area of land unit is expected to increase (Agrilyst, 2017). Soil-free farming techniques reduce unnecessary pressure on farmlands and can be conveniently practiced in urban areas. The characteristics and approaches of vertical farming were also discussed.

Horizontally stacked methods are employed on a large scale for commercial use and include sundry crops, mostly vegetables on a large scale. The available space within the stack levels determines the crops to be grown in most cases. Crops with a low canopy allow many stack levels, invariably yield is expected to be high, and profit is maximized. In addition to the stacking method, towers with multiple levels can also be employed. This takes into account the different conditions required for each crop. Several crops are cultivated using this technique and are highly suitable for controlled environments (Mok et al., 2014). Crop production by individuals can be done on balconies for spices and herbs. This method is constrained by space and, thus, may not be suitable for commercial applications (Beacham et al., 2019). The cylindrical growth units were similar to those of hydroponics. Crops were set after the other spiraling round a cylindrical housing with a nutrient supply system, while lighting was artificially supplied. More crop production per unit area was achieved relative to horizontal planting surfaces. Crop uniformity was achieved by including an artificial lighting system (Touliatos et al., 2016).

The benefits of vertical farming are understudied in terms of yield quantity, crop quality, energy management, and conservation. For vertical farming to be successful, certain factors must be considered, including crop suitability, cost, energy issues, and environmental impacts. Vertical farming is usually carried out in controlled environments; hence, energy use is higher than in field farming. This factor must be considered before proceeding to production although the yield increase is certain in comparison to the conventional system (Burrage, 1998). In some cases, vertical farming is premised on land availability and energy consumption. The environmental impact of production is minimal with the use of renewable energy sources in vertical farming systems. However, depending on the season, the footprints for carbon are likely to be higher in winter and summer, and greenhouse gas emissions are equally expected, while global warming due to the use of artificial lighting is considered. A primary constraint is the cost for business take-off since the focus for location is urban, and land prices are on the high side. Decisions about the location

between rural and urban areas are crucial. Rooftop glasshouse installation is a huge investment (Brin et al., 2016), which might not be kind to the investor's wallet. Options and choices, such as pre-existing buildings, could be considered to minimize cost. The production process should be optimized to rapidly increase profits. The differential costs of vegetables and fruits grown under vertical farming could be used to make profits and breakeven.

15.4.3 Breeding

Genetic enhancement of crops is of high significance in modifying crops to the severity of changes in climatic factors to ensure the sustainability of food production. Breeders have access to genetic diversity and good sources of germplasm to tailor breeding towards traits that can withstand extreme weather changes. Through unofficial seed networking, farmers can achieve genetic enhancement (Zohary, 2004). This has resulted in an enormous and rapid increase in yield, with tolerance to various degrees of stress. Domesticated plant species are genetically diverse wells that can serve as building blocks for innovation (Zhang et al., 2017a, 2017b). Wild crop relatives and landraces are large deposits of germplasm in the developing world, especially for dynamic environmental stressors (McCouch et al., 2013). However, the more ready-to-use materials that have gone through pre-breeding stages do not have sufficient diversity of genetic materials, the origin or domesticated regions of each crop contain genetic diversity, and in most cases, desired traits that can mitigate and support crops under extreme environmental conditions. Sundry techniques are used in breeding programs and for crop improvement. Protoplast fusion plus fertilization allows for a good genotype combination that was once regarded as incompatible (Tapingkae et al., 2012). The identification, isolation, and analysis of salient genes in crops that regulate tolerance are aided by plant genomics. This has allowed much work to be done on allelic variants. Several crop cultivars with characteristics of interest have been built through marker-assisted selection (MAS). Field trials are conducted in diverse locations to establish the tolerance of germplasms to environmental stressors for high-quality selection (Ghaffary et al., 2018).

15.4.4 Gene Editing

To improve global agricultural production, editing techniques must be applied to minimize the impact of climate change stress on crops to increase yield. For plants to withstand the impact of climate change, DNAs is modified at certain locations in the plant, which could be redundant, removed, or inserted. Editing can be achieved using TALENs, ZFNs, or the CRISPR/Cas technique (Khalil, 2020). The most

recent and modern method among the three is CRISPR/Cas. Some examples of genome editing are also discussed below:

- **Rice Plant.** Rice plants are primarily affected by drought and salinity stresses. The tolerant varieties were produced using CRISPR/Cas9. The genes responsible for salt stress were removed. Consequently, there was an increase in the grain yield of rice sown in soil with high salt content. An improvement in plant biomass has also been observed (Zhang et al., 2019). Similarly, the edited rice plants exhibited a high tolerance to drought. This is achieved through stomatal development, and stomatal density in rice plants is positively regulated (Yin et al., 2017). A gene-removal approach was used to reduce rice stomata. CRISPR/Cas9 has also been applied to flowering genes in rice plants to enable early flowering compared with traditional unedited plants. This will assist rice lines to survive and present high yields under extreme weather conditions (Li et al., 2017).
- **Banana Plants.** In anticipation of typhoons, storms, and severe winds from changes in climate patterns, banana plants are edited using CRISPR/Cas9 methods for high resistance to the negative impacts of intense weather conditions, which may result in lodging. Medium-height banana varieties have been built with edited genes for tolerance (Shao et al., 2020).
- **Maize Plants.** Maize plants are often disturbed by water stress during their flowering stage. To eliminate this, inclusion of drought tolerance genes through CRISPR/Cas9 was performed. This resulted in high-yielding maize varieties under water stress.
- **Resistance to diseases.** Owing to changes in climatic patterns, there is high temperature, humidity, and moisture. These factors tend to accelerate plant and animal diseases through severe incidence and frequency of occurrence. However, CRISPR/Cas9 resistance is also conserved in plants and animals. Wang et al. (2019) reported the resistance of tomato plants to powdery mildew infection. Editing provided significant resistance to infection. In the same vein, climate change has caused severe wheat powdery mildew. The edited wheat lines were found to be resistant to infection. Edited grapefruit varieties are equally resistant to citrus cankers (Jia et al., 2017). Furthermore, the resistance of cacao to *Phytophthora tropicalis* was elicited through editing (Fister et al., 2018).

15.4.5 Biostimulants and Biofertilizers

Biostimulants or biofertilizers consisting of chemicals or microbes are applied to crops or their underground structures. Commonly used biostimulants include microbial inoculants (beneficial bacteria and fungi), biopolymers, seaweed extracts, nitrogenous compounds, humic substances, plant extracts, and hormones (Malik et al., 2021). They can be applied to soil or as foliar sprays, depending on their composition and goals (Shah et al., 2018). Various biostimulants, including bacteria, fungi, and biomolecules, have been tested under controlled conditions to reduce

climate change-related stress and to improve plant resilience and productivity. Recent studies have extensively analyzed the sources and benefits of biostimulants in mitigating abiotic stress. This section discusses the commonly used biostimulants in controlled environments to alleviate abiotic stress caused by climate change as outlined below:

- **Organic amendments.** Compost and biochar are widely used as organic amendments in protected ecosystems owing to their cost-effectiveness and availability. Biochar is a promising climate change mitigation strategy because it can sequester soil organic carbon and reduce nitrous oxide (N₂O) emissions when used as a soil amendment (Xu et al., 2019). Compost provides several agricultural benefits including carbon sequestration, which limits CO₂ emissions. Research has shown that composts gradually improve tomato yield and enhance soil properties (Koul et al., 2022). Additionally, organic fertilizers, such as compost, improve soil water retention even under limited water conditions (Elanchezhian et al., 2020). Amankwaa-Yeboah et al. (2023) found that compost increases water retention and boosts plant growth under water-scarce conditions.
- **Bacteria and Fungi.** Endophytic microorganisms form symbiotic relationships with plants and reside in seeds, foliage, branches, and roots throughout their life stages. These microorganisms enhance plant growth by facilitating nitrogen fixation, phytohormone release, and nutrient acquisition. In turn, plants sustain endophytes by secreting root exudates that provide essential energy (Kandel et al., 2017). Plant growth-promoting rhizobacteria (PGPR) inhabit the rhizosphere and enhance plant growth, while reducing susceptibility to phytopathogens (Kloepper et al., 2004). Studies have highlighted their potential for alleviating climate change-related stress (Begum et al., 2019). PGPR are crucial for the production of key plant hormones, such as auxins, cytokinins, and gibberellins, which modify root architecture and enable crops to better withstand abiotic stresses, such as nutrient deficiency, drought, heavy metal toxicity, and salinity (Inbaraj, 2021). Auxins such as indole acetic acid (IAA) promote cell elongation and enhance root system growth and lateral root formation, which improves water and nutrient uptake (Inbaraj, 2021). Some PGPR release exopolysaccharides (EPS) that protect themselves and their host plants from adverse environmental changes (Morcillo & Manzanera, 2021). Under environmental stresses, such as drought, PGPR produce secondary metabolites, including volatile organic compounds, to boost plant growth and reduce drought stress (Ho et al., 2017).
- **Other molecules.** Other compounds that serve as biostimulants include secondary metabolites, amino acids, and silicones (Table 15.1). Rossi and Huang (2022) documented the effectiveness of external β -carotene application in enhancing plant resilience to heat stress. Similarly, Tonhati et al. (2020) demonstrated the protective effects of L-proline against heat stress. Lin et al. (2019) found that glycine betaine spray reduces the adverse effects of water deficit stress. Moreover, silicon (Si) has also been reported to alleviate the detrimental impacts of a variety of stresses (Biju et al., 2017).

Table 15.1 Application of biostimulants and biofertilizers to mitigate climate changes stress and produce climate-resilient crops

Biostimulants	Crops	Stresses	Findings	References
– β -aminobutyric acid	<i>Quercus robur</i>	Elevated CO ₂	– β -aminobutyric acid increased plant root system and enhanced plant resistance to powdery mildew	Sanchez-Lucas et al. (2023)
– Livestock manure + biochar and ash	<i>Triticum aestivum</i>	Elevated CO ₂	– Organic amendments reduce the emission of CO ₂ while chemical fertilizers increase its emission	Doyeni et al. (2023)
Organic compost	<i>Solanum lycopersicum</i>	Water deficit	– Organic compost enhances plant biomass and crop water productivity at highly deficit irrigation systems compared to NPK fertilizer	Amankwaa-Yeboah et al. (2023)
– β -carotene	<i>Agrostis stolonifera</i>	Heat stress	– β -carotene application suppressed heat-induced leaf senescence, as demonstrated by an increase in turf quality and leaf chlorophyll content as well as a reduction in electrolyte leakage and oxidative stress	Rossi and Huang (2022)
– Silicon	<i>T. aestivum</i>	Drought and heat stress	– Si treatment has the potential to mitigate the detrimental effects of individual and combined stress of drought and heat by improving physiological response	Ashfaq et al. (2022)
– <i>Rhizophagus irregularis</i> (AMF)	<i>Hordeum vulgare</i>	Elevated CO ₂	– AMF substantially increased phosphorus uptake at elevated CO ₂ and prevented phosphorus dilution	Thirkell et al. (2021)
– L-proline	<i>S. lycopersicum</i>	Heat stress	– L-proline applications resulted in lower hydrogen peroxide contents and improved titratable acidity as well as the overall fraction of average total soluble solids	Tonhati et al. (2020)
– Amino acids	<i>S. lycopersicum</i>	Salinity	– Treatment of tomato plants with amino acids palliate the negative effects of salinity stress	Alfosea-Simón et al. (2020)

(continued)

Table 15.1 (continued)

Biostimulants	Crops	Stresses	Findings	References
– <i>Azospirillum brasilense</i> – <i>Pantoea dispersa</i>	<i>Capsicum annuum</i>	Heat stress Elevated CO ₂	– PGPRs promoted plant growth and physiological processes under high temperatures and CO ₂	Pérez-Jiménez et al. (2019)
– Betaine – Chitin – Combination of betaine and chitin	<i>Zea mays</i>	Water deficit	– Betaine (50 mM) and chitin (2 g/kg) treatments significantly elevated plant biomass and boosted the water-stress tolerance of the maize under water deficit compared to controls	Lin et al. (2019)
– Protein hydrolysates	<i>Z. mays</i>	Cold stress	– Application of a protein hydrolysate increased the performance of chilled maize plants, as demonstrated by leaf gas exchange, photosynthetic pigment content, and chlorophyll fluorescence, but did not affect their growth	Cholakova-Bimbalova et al. (2019)
– Endophytes from the genera of <i>Penicillium</i>	<i>Hordeum secalinum</i>	Salinity	– At 75 mM NaCl endophyte-associated increase in early growth, grain dry weight, shoot dry weight, root dry weight, number of tillers, number of heads and number of grains – Above 75 mM NaCl endophytes failed to enhance plant tolerance to salinity stress	Murphy et al. (2018)
– Acibenzolar- <i>S</i> -methyl	<i>Agrostis stolonifera</i>	Drought and heat stress	– Acibenzolar- <i>S</i> -methyl (ASM) treatment resulted in improved heat or drought tolerance, as demonstrated by higher overall turf quality, relative water content, and chlorophyll content compared to the untreated control – ASM application resulted in up-regulation of ATP synthase, HSP-20, PR-3, and Rubisco in plants exposed to heat stress, and greater accumulation of dehydrin in plants exposed to drought stress	Jespersen et al. (2017)

15.4.6 Smart Irrigation Systems

Projections in world population growth are expected to boost food demand and invariably, food production. There is an urgency in increasing productivity;

however, depletion of land and water coupled with weather extremes is a factor that slows down agricultural productivity through shortages of water or flooding, which necessitates the application of smart technologies to increase production output to equate the global demand for food (Alexandratos & Bruinsma, 2012). Smart technologies and automated systems allow optimization of inputs for quality and quantity improvements (Elsayed et al., 2021) and thus mitigate predicted food crises (Doshi et al., 2019). Reliable food production is expected through field irrigation and up to about 40% of the world's food production is contributed by irrigated farmlands. The irrigation techniques were designed specifically for each crop. Water supply efficiency is important for agricultural sustainability. In regions with water scarcity, it is pertinent to have techniques for adaptation to ensure accessibility. Primarily, the smart irrigation system must be economically feasible, fit into the field topography, and be highly comparable to the farm setup. Several smart irrigation techniques are available, and a few are mentioned below.

- **Moisture-reliant irrigation.** These were furnished with volumetric and tensiometric units, respectively. There is a relationship between the water characteristics of a specific soil type and the units. The operation of volumetric units may be controlled by dielectric or neutron sensors, whereas tensiometrics are water-holding units that operate under pressure. The moisture-reliant system identifies water stress in the field and swings it into action by irrigating the field. The data provided were applied in the estimation of extreme dryness, flooding, and erosion of the farm field. Negligible errors were noted relative to the variability of the soil.
- **Automated plant-reliant systems.** A moisture sensor was built to irrigate plants on a regular basis. The system comprises a timer and op-amp comparator in a circuit. Environmental variables determine hardware constituents (Darshna et al., 2015). The water stress of the crops in the field was evaluated, and the field was irrigated if needed.
- **Wireless real-time sensor arrays.** The application of this technique is limited because it is crop-specific. Irrigation is properly scheduled for high-water-efficiency use in a particular crop for high-water-efficiency control. The conditions for use are tailored to the critical water scarcity times. High importance is strictly related to the quantity of irrigated water, its effect on crops, and its frequency (Gamal et al., 2023).

15.4.7 Adaptive Crop Management

Increases in variability and drastic changes in weather seasonality are characterized by fluctuations in precipitation, temperature, humidity, and dry-spell frequencies (Nyasimi et al., 2014). These extremities cause degradation, reduced soil fertility, and risks to agriculture, culminating in colossal loss in crop yield. For farmers to cope with the fallout of climate variability, they must change their basic traditional farming practices. New methods of practice include the use of tolerant crops,



Fig. 15.2 Innovative techniques applied in protected environments to mitigate climate change and produce crops with climate resiliency

control of soil fertility, intercropping, and crop rotation (Manda et al., 2016). With the practice of all these combinations, productivity improvement is expected, irrespective of the impact of extreme weather. The smallholder sector is more flexible and benefits from this diversification (Faurès et al., 2013). Crops of the same or dissimilar species may be intercropped or rotated after each other to minimize uncertainties in weather variability. This approach is cost-efficient and ecologically practical. Diversified farmer fields are more stable in terms of soil fertility, pest management, and most importantly, yield. Makate et al. (2016) established that crop diversification increases the stability of farm production, yield, and farmers' income. The significance here is that diversification is an adaptation technique that has proven positive under weather variability. Adjustments can be made instantaneously when there are changes in the weather variables at the discretion of the individual farmer. Alternatively, it may be through government-planned procedures of infra-structural development and information to farmers. Diversification is a salient method for the adaptive adjustment of weather variability. Figure 15.2 summarizes the innovative techniques mentioned above.

15.5 Conclusion and Perspectives

This chapter discusses the impact of climate change on crop production and explores innovative techniques for developing climate-resilient crops in protected environments. The authors highlighted the importance of developing new farming techniques to help crops thrive despite environmental stress factors. Protected cultivation, which involves shielding crops from external environmental factors, is a popular farming technique that allows growers to regulate environmental conditions, thereby resulting in improved plant performance. We explored various technologies used in protected environments to address the effects of climate change and improve plant production and quality, such as sensors and automation, advancements in breeding and genetic editing, biofortification, smart irrigation, and adaptive crop management. Additional investigations are necessary to develop innovative methods with high effectiveness and minimal expenses for application at both small and large scales.

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Chapter 16

Small-Scale Postharvest Practices for Strengthening Sustainability in Handling Horticulture Crops



Vijay Yadav Tokala

16.1 Introduction

The global population has grown significantly, with the current population exceeding three times the size it was in the mid-twentieth century. It is estimated that the global population is set to expand by nearly 2 billion individuals over the next three decades, reaching 9.7 billion by 2050, and potentially peaking at close to 10.4 billion in the mid-2080s (United Nations, 2022). To suffice the food demand of the population in future, it is estimated that food production should increase by 60% worldwide, when compared to levels recorded between 2005 and 2007, in addition to promoting fairer access to all. Moreover, on the other hand, it was estimated that globally, about 14% of the food, valued at US\$400 billion is lost on an annual basis between harvest and the retail market in the world (FAO, 2022). At the same time, an estimated 17% of food is wasted at the retail and consumer levels (UNEP, 2021). In 2011, the United Nations Food and Agriculture Organization (UNFAO) estimated that globally, about one-third of all food produced for human consumption is lost or wasted. Postharvest losses occur at various stages of the supply chain, from farms to household consumption, negatively impacting the global economy, the environment, and sociological aspects. These losses not only diminish farmers' income and increase the cost of produce for consumers but also represent a waste of resources such as water, land, and energy used to cultivate crops that never reach the consumer. The resources and investments used to produce lost or wasted food are essentially squandered, highlighting the need to address losses to enhance food and nutrition security and promote sustainable food systems. Implementing sustainable postharvest practices, such as improved cooling and storage facilities, can help to

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reduce these losses, ensuring that a larger percentage of harvested crops contributes to food availability.

The postharvest losses have significant implications for food security, nutrition, and the sustainability of food systems, affecting their ability to provide high-quality and sufficient food. Therefore, mitigating postharvest losses presents a sustainable solution to combat hunger and malnutrition worldwide, while also reducing carbon emissions. With the climate crisis altering environmental conditions, it is imperative to address postharvest losses through a climate perspective to ensure the resilience and sustainability of food systems. Despite being a longstanding issue, global FLW has gained increased attention and visibility in recent years due to its profound impact on food system sustainability. Various organizations such as FAO, the World Bank, ReFed, WRAP, the World Wildlife Fund (WWF), WFLO, GAIN, and FES have conducted numerous studies on losses, consistently revealing alarmingly high postharvest losses for horticultural crops. For instance, SAVE FOOD gathered FLW data for Kenya on mangoes and bananas, showing postharvest losses averaging between 20% and 50% during the period between harvesting and retail marketing, aligning with statistics presented in UN FAO SAVE FOOD promotional materials.

Environmental sustainability in postharvest management also encompasses the reduction of the carbon footprint associated with horticultural supply chains. The use of refrigerants in cooling systems, the energy required for storage facilities, and the emissions from transporting goods over long distances all contribute to the environmental impact of postharvest management. Sustainable practices, such as the proper handling, adoption of renewable energy sources, and optimization of logistics, are necessary to minimize these impacts. Additionally, packaging materials used in the transportation and marketing of horticultural products often result in plastic waste, prompting the need for biodegradable or recyclable alternatives to reduce environmental pollution. The majority of farmers globally are smallholders, operating on small land holdings, which underscores their critical role in sustaining local food systems and economies. These small-scale farmers contribute significantly to the world's agricultural output, often employing traditional and sustainable farming practices that are vital for biodiversity. Small-scale producers often lack the resources and knowledge to implement advanced postharvest techniques, which can lead to disproportionate losses and economic hardship (Fan & Rue, 2020).

It is critical to analyze the potential of technological intervention or approach while considering the context in which the user utilizes and the suitability with the different characteristics of the user. For example, certain technology might have proved to be a great success among the large-scale growers of specific locations; however, it might be difficult for smallholder farmers to acquire, use, and manage. The technology over time may not even prove to be economically feasible and not sustainable for the other location (Ridolfi et al., 2018).

Capacity building, knowledge transfer, and investment in infrastructure are essential to empower these farmers, enabling them to improve the shelf life of their produce, gain better market access, and ultimately enhance their livelihoods. By addressing all these dimensions cost-effectively, postharvest management can

contribute to the food system more sustainably. This chapter discusses sustainable small-scale operations for postharvest management of horticulture crops.

16.2 Harvesting and Postharvest Field Operations

16.2.1 *Harvesting at the Right Stage*

Harvesting is an important operation in horticultural crop production and improper methods lead to huge losses to growers due to damage to crops by bruising caused by impact, vibration, or compression. The right time to harvest a crop is usually when the crop is at the desired maturity stage and sufficient labor and transport facilities are available. The decision as to when to start harvesting will largely depend on the weather conditions on that day and the state of the market demand. However, the flexibility of the decision based on the market demand depends upon the crop. Some crops such as tuber crops can be harvested and marketed over a long period or if the weather conditions permit the crop can be stored on the farm to wait for the desired price in the target market. In the case of more perishable crops such as soft berry fruits, they must be harvested and marketed as soon as they attain the desired maturity. Harvesting too early before complete development of flavor or respective varietal characteristics or too late when they grow too large, fibrous, or full of hard seeds, both practices affect postharvest quality of produce. In the case of the horticulture crops, when the whole lot is harvested all at once there is a high probability to have a significant proportion of produce being either under-mature or over-mature.

Harvesting the produce at proper maturity is a critical factor in deciding the post-harvest quality and immature fruit will develop very poor quality and erratic ripening. If the produce is to be shipped to a distant market, the fruit can be harvested at a mature but unripe stage. The harvest/maturity indices are different for each crop and can be subjective to decide the right stage of the harvest to meet market requirements and ensure adequate shelf life for the distance to market. Using a maturity index as a standard and harvesting the crop multiple times will greatly reduce pre-sorting losses. The harvest maturity can be judged using different instruments like refractometer to measure total soluble solids (Brix) or a hand penetrometer to measure fruit firmness (Shezi et al., 2023).

The factors like best time of the day must also be considered while making decision on harvesting the produce. The aim is to dispatch the produce to the market in the best possible condition to get the best price and, as cool as possible in a properly packed condition free from damage, defects, and decay. The basic thumb rules to be considered while harvesting the produce are as follows (Thompson et al., 2001):

- Harvest the produce at the coolest part of the day, which is either early morning or late afternoon.

- Avoid harvesting when the weather is wet by dew drops or rain. There are chances that the wet produce will overheat if not well-ventilated, and it will be more likely to be prone to decay. Some citrus fruits develop symptoms such as oil spotting and rind breakdown.
- Protect the harvested produce in the field by putting it under open-sided shade if not transported immediately. The produce exposed to direct sunlight will accumulate high amounts of field heat. For example, the produce exposed to direct sunlight can become 4–6 °C warmer than air temperature.

Produce for nearby markets could be harvested early in the morning. For the distant markets, it may be advantageous if the produce is harvested in the late afternoon and transported to the market during the night or early morning when air temperatures are relatively low. Using improper containers can induce mechanical injuries and accelerate water loss, reduce nutrient levels and increase the rates of respiration and ethylene production leading to quick deterioration and increased susceptibility to decay-causing pathogens.

The harvest containers should be clean with smooth inside surfaces free of rough edges. Plastic buckets or stackable plastic crates, while initially expensive, are durable, reusable, and easily cleaned. If baskets must be used, they should be woven “inside out” with the stubs of the beginning and end of each cane on the outside of the basket.

Manual harvesters should be well trained with the proper methods to harvest the crop with minimum damage and waste (Fig. 16.1). They should be able to correctly recognize the right maturity stage of the product based on the target market demands. Pickers should harvest with care, by snapping, cutting, or pulling the fruit or vegetable from the plant in the least damaging manner. When produce is fully developed, a natural break point develops at the point where the stem and the stalk meet. Harvesters should pull upward while holding the produce firmly but gently along the breakpoint.

The knife tips should not be pointed but preferably be rounded to minimize accidental scratches on fruit and reduce damage to plant parts affecting growth in case of the perennial plants. Sharp knives and clippers should be used, and the harvesters should be trained to handle the harvested produce gently and not throwing the

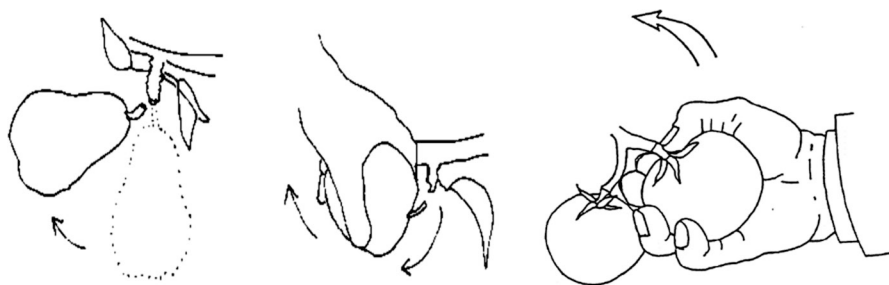


Fig. 16.1 Picking the fruit to avoid damage to the produce. (Source: FAO, 1989)

produce into harvest containers. De-accelerating chute made of woven matt, heavy fabric, or canvas can be used to reduce impact injuries in the fruit.

Produce should sustain the least amount of mechanical harm during harvesting procedures. Crop losses can be decreased with gentle digging, picking, and handling. The following recommendations are made for pickers while harvesting horticulture produce:

- To minimize any injuries in the fruit induced by fingernails during harvest and also to protect the fingers of pickers, cotton gloves should be worn during picking.
- Pickers should trim their fingernails short to avoid injuries to the fruit.
- During harvest, jewelry such as bracelets and rings should not be worn.
- Ideally, picking containers should be shallow, wide, and stackable to avoid excessive weight and bruising of the produce at the bottom of the container.
- Picking containers should not be overfilled as the produce may suffer compression injury.

16.2.2 Packhouse Operations

The appropriate packhouse operations are crucial for the retention of produce quality and extending the holding life. These operations can be as simple as transferring the produce from the field into the transport vehicle/container but do have a significant effect on the physiology and ultimate quality of the produce. A variety of handling practices, such as sorting, washing, cleaning, and grading based on size, quality, or color, waxing and packing, are involved and the steps can vary based on the produce being handled.

The provision of shade to prevent direct sun exposure is essential throughout all the packhouse operations. It can be created using simple materials such as palm leaf fronds, a plastic mesh or canvas sheet hung from temporary poles, or by a permanent roofed structure. The produce is brought to the packers in picking containers usually in the simplest packaging facility as soon as it has been harvested. After sorting and grading, the produce is immediately put into the appropriate delivery containers for the next step of the supply chain. To reduce losses and ensure quality, each employee at this stage must be educated about produce defects, grades, and size specifications, and packing techniques as per the produce requirements and consumers' demand. The packhouse can have additional operations and staff members skilled in certain jobs as the size and complexity of operations increase.

In the case of some tuber and bulb crops, curing before handling, packing, or bulk storage is an essential step. Curing is essential for roots and tuber crops like sweet potatoes, potatoes, and cassava roots. Curing involves storing the harvested crop in a humid and warm environment to help heal the harvest wounds and surface damage that occurred during the field operations. For bulb crops like onions and garlic, curing involves a few layers of peelings and drying of the neck to protect the

crop from water loss and decay during handling, storage, and marketing. Curing roots, tubers, and bulb crops will increase storage life and protect quality during storage and marketing. For example, well-cured sweet potatoes store for 7 months at 15 °C, and well-cured potatoes store for up to 10 months at 5–12 °C. While, uncured bulb crops can lose 35% of their initial weight in 1 month. Basic operations in the packhouse include:

- (a) **Dumping:** The produce is transported to the packhouse in harvesting bins or containers from the field. The first process in the packhouse is referred to as “dumping.” Whether dry dumping on a surface or wet dumping in the water-assisted techniques, dumping must be done gently. Padded, sloping ramps, or conveyor belts can reduce impact injury during dry dumping. Wet dumping can decrease impact bruising and abrasions. It is important to chlorinate (100–150 ppm) the water used for wet dumping or washing to stop contamination from spreading from one item to another. For optimal results, the wash water’s pH level should be maintained between 6.5 and 7.5. For some produce, such as pears, salts (sodium silicate or sodium sulfate) must be added to the water to increase the specific density and assure fruit floatation.
- (b) **Sorting:** Sorting the produce before packing eliminates low-quality and damaged produce thereby reducing packing costs of high-quality produce. As sorting also takes care of misshaped, decayed, diseased, and injured fruits, the losses during post-packing operations are also reduced. The objective of sorting is to remove injured, decayed, over-ripe, diseased, decayed, and defective produce before cooling or additional handling. This will save efforts, money, and energy by not handling the culls along the supply chain and removing decaying produce will limit the spread of infections to others.

The sorting tables and stools should be set at a level comfortable for sorters to reduce fatigue. To improve the capacity of the sorter to identify flaws and reduce eye strain, provide good illumination, and use dull, dark conveyor belts or table surfaces. When using a conveyor system, the product should move at a convenient speed for the sorters to complete their task effectively. Supervisors should be able to see under- and over-sorting right away.

- (c) **Cleaning:** The type of cleaning depends upon the commodity. In the case of crops such as bananas and mangoes, washing is required to clean off latex stains. For kiwifruit and avocado, dry brushing is appropriate. When water is used as a medium to clean the produce, sanitation has to be taken care of to control the spread of disease from one item to another and to avoid the building up of spores in wash water or the packhouse environment. Chlorine treatments (100–150 ppm) when used in the wash water prevent pathogen buildup in the wash water during packhouse operations.
- (d) **Waxing:** It is usual practice to wax immature fruit vegetables like brinjal (egg-plant), cucumbers, and summer squash, mature fruit vegetables like peppers, and tomatoes, as well as fruits like apples and peaches. Food-grade waxes can assist in preventing water loss during handling and marketing by replacing some of the natural waxes that are eliminated during washing and cleaning

procedures. Waxes also cover the minor injuries on the fruit surface, act as carriers for fungicides or improve the cosmetic appearance of the product. The most common types are mineral-oil-based waxes and natural waxes such as carnauba or bee wax. Both can be formulated as water-based emulsions or with a solvent. Produce that has been waxed with water emulsions must be allowed to completely dry before further handling to achieve proper wax properties. Convention hot air dryers are commonly used for this purpose.

- (e) **Grading:** Grading is an important process because the presentation of produce, an aspect of quality, is often judged based on uniformity. Uniformity is important as it presents a standard product for handling and marketing. Fruits when graded fetch relatively better prices per unit as the quality grade increases. Off-grade fruits should be removed from the packhouse lines as early as possible. The grading can be based on size, weight, color, shape, and maturity, with the specifications often provided by the buyer.

In most of the low-input packhouses, manual sizing is still commonly practiced. Operators should be educated to choose the desired size and to either pack the products immediately into containers or gently drop the chosen produce into a bin for packing later on. Utilizing common size gauges allows for subjective (visual) sizing. For convenient reference, examples of the smallest and biggest permissible sizes, or visually superior quality for each product can be put in the operator's line of sight. Several goods can be graded using handheld devices. The grading standards can be custom-made based on the market demand and importers' requirements if the produce is being exported.

There are different types of mechanical sizers available suitable for small-scale operations. A long, sloping tray with a sequence of convergent apertures (biggest at the top, smallest at the bottom) makes up one kind. Round commodities respond well to this kind of sizer. Most commodities may be sized with the help of other sizes, which are conveyors with chains or plastic belts with varying-sized apertures. Utilizing a series of diverging bar rollers is another straightforward mechanical sizing technique. Here, a product of the smallest size falls through the rollers first to a sorting belt or bin, while a produce of the bigger size falls between increasingly more divergent rollers.

16.2.3 Packaging

Packaging may help or hinder achieving the best quality and storage life across the whole handling system. The main objectives of the packing are to enclose the produce while protecting it from mechanical, biological, and environmental damages. Packaging materials should allow for ease of transport while being compatible with the different storage environments used for certain produce. The displays, labels, and information on the packages can also provide scope for enhanced marketing. Packages or containers must be sturdy enough to avoid collapse and must include

vents (openings in the package, of approximately 5% of the area per side) to allow proper aeration. Waxed cartons, wooden crates, or solid plastic containers are preferable over plastic bags or open baskets as the latter offers little protection to the product when piled. Produce can occasionally be protected further by strengthening or lining locally built containers. Though initial investment for the waxed cartons, wooden or rigid plastic crates is high, they are economical when utilized for extended periods. These reusable containers can withstand the high relative humidity present in the storage environment (Table 16.1). Using soft cardboard liner in these cartons reduces abrasion injuries (Fig. 16.2). The containers should not be filled too loosely or too tight with the produce. The produce vibrates against each other and causes bruising when packed loose, while over-packing causes compression/impact bruises in the fruit (Fig. 16.4). Soft cardboard trays are often used to stabilize round produce items (Fig. 16.2). The shredded newspaper is the most used cushioning material for horticulture produce (Fig. 16.5).

When the packages are handled in a storage atmosphere with high humidity, the strength of cardboard packages is reduced and they tend to collapse, offering little to no protection. In such a case, the item within the damaged package must bear the whole weight of the overhead load. In such cases, the objective of packing providing cushion and immobilizing the commodity is not met.

During palletization, the produce is stacked up and arranged systematically on the pallet. In some cases, they are held together on the pallet by cling wrap or other means. The forklift can then raise whole thing as a unit to transport, store, load, or unload the produce (Fig. 16.3).

16.2.3.1 Choosing a Packaging Material

The physical and physiological properties of different horticulture produce are diverse, and this makes choosing the appropriate container a complex decision. Various factors such as price, durability, reusability, protection, and environmental sustainability have to be considered while choosing the right container. Some of the factors to consider while selecting a container are provided here.

Table 16.1 Comparison of different containers

	Corrugated fiber board	Returnable plastic crates	Expanded polystyrene	Corrugated plastic board	Wood
Damage protection	Low	Best	Best	Best	Best
Recycle	Best	Best	Low	Good	Low
Reuse	Low	Best	Low/good	Low	Low
Labeling	Best	Low	Good	Good	Good

Fig. 16.2 Soft cardboard liner in these cartons to reduce abrasion injuries



Fig. 16.3 Apple fruit packed in plastic crates arranged on wooden pallets



Containing

1. Desired holding capacity.
2. Ease in handling.
3. Design complying marketing demand and other standards.
4. Easy to palletize.

Protection

1. Stable when stacked and do not deform when stacked with consistent dimensions.
2. Proper air circulation.
3. Keep produce safe from impact injuries during storage, handling, transport, and retail sale.



Fig. 16.4 Over-packing vegetables in soft-sided packages like sacks causes compression bruises



Fig. 16.5 Shredded paper used as cushioning material while packing pomegranate

4. Smooth surface material with no intruding/protruding sharp edges.
5. Possibility for usage of liners.
6. Easy to sanitize/clean.
7. Protect from theft when covered.

Branding

1. Feasibility to affix/tag labels.
2. Scope for advertisement and mention the brand name.

Marketing

1. Appealing appearance for consumers.
2. Comply with the customs control norms.

Cost and Miscellaneous

1. Reasonable purchase cost.
2. Durable/deterioration.
3. Repairable.
4. Consistent supply of the material.
5. Low cargo volume when empty.
6. Possibility for local manufacturing.
7. Ease in transportation/fitting in pick-up or handcart.

16.2.3.2 Retail Packaging

These are consumer units of smaller sizes and designed to hold 1/2 dozen to 1 dozen fruits or 1/2 to 2 kg of fruits or vegetables. The package protects and advertises food in convenient quantities for retail sale and home storage. This includes flexible plastic bags, punnets, mesh bags, and cardboard or molded plastic trays. Plastic film wrapping also has the potential to change the environment around the produce (this is known as modified atmosphere packaging or MAP). When restricting the airflow, MAP-wrapped products breathe normally, which causes the air inside the package to become higher in carbon dioxide and lower in oxygen. Decreased water loss is a significant advantage of using plastic wraps, bags, or sheets. Most of the horticultural commodities will benefit from lower oxygen and higher carbon dioxide concentrations to enhance the life of produce but the variations between the healthy and hazardous quantities of these gases for each produce are unique and relatively small. Therefore while employing these technologies, extreme caution must be exercised to maintain the cold chain and stay within the safe limits for MAP suited for the produce.

16.2.3.3 Cushioning Material

The cushioning materials are used for packaging fruits to reduce impact bruises (Fig. 16.5). Materials such as straw, banana leaves, sawdust, and paper shreadings are relatively sustainable than plastic/polystyrene foams, among the commonly used materials. Any materials used as cushioning should have resilient properties and can dissipate the heat of respiration of the produce. They should be physiologically inactive and free from microbial load or pests.

16.2.4 Transportation

Transporting horticultural products involves using various transportation methods to move goods from production sites to consumers. The primary aim is to transport perishable items while maintaining their quality. The fresh produce is vulnerable to physical harm and contamination while in transit. Therefore, a well-structured plan is essential for transporting produce from the farm to the end user. Proper procedures and controls need to be implemented throughout the transportation process to ensure that the products reach their destination in a good and safe condition for consumption.

The vehicles should have adequate insulation to preserve cool conditions for pre-cooled products and be well-ventilated to facilitate air circulation along the produce. When loading produce for transport, it should be stacked carefully to minimize damage, secured properly, and kept in a way that allows air to flow through to help with cooling during transit. Nighttime or early morning travel can reduce heat stress on vehicles transporting produce. Drivers handling produce shipments should receive training on loading and handling procedures to maintain optimal storage temperatures and reduce spoilage risks during transport.

Several factors should be considered for efficient transportation, including managing temperatures effectively during long-distance journeys. Proper stacking of loads to allow air circulation is crucial to dissipate heat generated by the produce and external sources. Avoid overloading to prevent postharvest losses due to compression, overheating, and increased water loss. Using sturdy packaging can help reduce mechanical damage during transportation. Proper alignment of containers is important to maintain stacking strength, especially focusing on the corners of corrugated boxes. Vibration damage can be minimized by utilizing air suspension systems.

For open loads, insulation and cushioning should be provided to protect bulk goods. Designing wind catchers can facilitate air movement within the vehicle during transport. Various pallet covers, such as polythene covers and lightweight insulated covers, are available to shield cooled products from dust, moisture, and temperature fluctuations during handling and transportation.

16.3 Cold Chain Operations

16.3.1 Precooling

Fruits and vegetables when harvested from parent plant are still living tissues, which received the supplies of water and nutrients from plant before harvest. The water content of fruits and vegetables is relatively high when harvested which gives them a shiny appearance and crispy texture. Once harvested, the supply of water and

nutrients is cut off, and they start accumulating heat from physiological processes such as respiration (Holcroft, 2015).

Temperature management is the critical factor to ensure postharvest quality and safety between harvest and consumption. Low temperatures reduce the rate of physiological activities, elongate shelf life, retain quality, and reduce losses (Kitinoja & Kader, 2015). Precooling is a process that is to be done immediately after harvest, and before transporting into low-temperature storage or market, to remove field heat and cool the produce (sometimes by up to 87% of its initial temperature (to 1/8th of initial temperature)). The field heat is the difference in temperature between harvested produce and the storage temperature of that produce. An hour's delay at field temperature conditions (~35 °C) can reduce the shelf life of produce by about a day even if they are later handled at optimum storage conditions (FAO, 2011).

Pre-cooled produce tends to retain more moisture at postharvest stages, causing reduced skin shriveling and wilting during storage (Table 16.2). This is crucial for maintaining profits, especially when fruits are traditionally sold by weight (Wills & Golding, 2016). The firmness and crispness of apples are key sensory attributes. Enzymes responsible for fruit softening become more active as the core temperature of the fruit rises, resulting in increased softening as the temperature increases (Makule et al., 2022).

Table 16.2 Comparison of different precooling methods

	Room cooling	Forced air cooling	Hydrocooling
Definition	The produce packed in ventilated crates, bins, or sacks is loaded into a cold room, and cold air is circulated	Improvement of traditional room cooling where the cooling efficiency is increased by installing fans to enhance the airflow rates through the produce	Produce is cooled by direct contact with cold water
Cooling time range (hours)	20–100	1–10	<1
Water contact	No	No	Yes
Energy efficiency	Low	Low	High
Advantages	Easy, low maintenance	High efficiency, faster than room cooling	Fast and uniform cooling, no moisture loss from fruits, less expensive, includes chemical treatments to control storage diseases
Disadvantages	Uneven cooling, slow process	Uneven cooling	High chances of microbial cross-contamination, water being circulated must be disinfected and chlorinated (100–150 ppm)

16.3.1.1 Benefits of Precooling of Harvested Fruits and Vegetables

- Decrease respiration and ethylene production rates.
- Slows down ripening and reduce perishability.
- Minimize transpiration and associated water loss and shrinkage.
- Decreases microbial activity.
- Reduces quality deterioration, viz., browning, texture loss, flavor degradation, and nutrient loss.

16.3.1.2 Options for Precooling

- Hydrocooling by direct contact with water.
- Vacuum cooling, forced air cooling, and top icing.
- Typically utilize mechanical refrigeration, with some low-cost alternatives available for areas with limited electricity access or high costs.
- Alternative traditional systems for precooling include shade usage, night air ventilation, radiant cooling, underground cooling, and evaporative cooling.

16.3.1.3 Selection Criteria for the Precooling System

1. Characteristics of crops (chilling sensitivity, water tolerance, geometry, and thermal properties).
2. Quantity of produce to be pre-cooled (per day or hour).
3. Initial temperature compared to the target temperature.
4. Packing configuration and stacking setup.
5. Capital and operational expenses of the precooling system.
6. Expected financial benefits from implementing precooling techniques.

16.3.2 Storage

Various storage methods can be utilized to maintain the quality and prolong the shelf life of produce. The main goal of any storage technique is to slow down the metabolic processes and respiration of the produce without adversely affecting its natural metabolism, which could lead to undesirable changes. Preserving perishable food items at lower temperatures helps in reducing respiration rates, prolonging shelf life, delaying ripening, and preserving product quality. Produce designated for storage should be of high quality, meaning it should be undamaged and free from disease. Damaged produce tends to lose moisture more rapidly and has a higher likelihood of decay during storage compared to undamaged produce.

It is crucial that produce intended for storage is harvested at the appropriate maturity level, avoiding over-ripeness or under-ripeness. Before storage, it is essential to precool the produce (e.g., through shading or hydrocooling) to eliminate field heat. Root, tuber, and bulb crops should undergo curing before being placed in storage. While certain cultivars naturally have longer storage capabilities than others, the storability of produce primarily hinges on its respiration rate (metabolic activity).

Points to be considered for effective storage practice:

1. High-quality produce free from damage, disease-free, and at the proper maturity level should be stored.
2. Understand the storage requirements for different commodities and adhere to recommendations regarding temperature, humidity, and ventilation.
3. Store at recommended cold storage temperatures to avoid chilling and freezing injuries.
4. Storage areas or stack containers should not be overloaded.
5. Ensure adequate ventilation within the storage space.
6. Maintain cleanliness in storage rooms.
7. Keep the storage areas clean and pest-free.
8. Use well-ventilated containers that can withstand stacking without exceeding their capacity.
9. Monitor storage room temperature by placing thermometers at various locations.
10. Avoid storing ethylene-sensitive produce alongside items that emit ethylene.
11. Refrain from storing products known for strong odors (e.g., apples, garlic, onions, cabbages, and potatoes) with odor-absorbing items.
12. Regularly inspect stored produce for signs of damage, water loss, disease, and injury.
13. Remove damaged or diseased produce promptly to prevent the spread of diseases.

Ethylene-Producing and Ethylene-Sensitive Horticulture Commodities

- Commodities producing ethylene: apple, banana, pear, peach, tomato.
- Ethylene-sensitive commodities: lettuce, cucumber, carrot, Irish potato, sweet potato.

Cold storage plays a key role minimizing postharvest losses by maintaining the required temperature conditions from harvest to consumption. A cold chain means temperature-controlled supply chain encompassing various processes and equipment to ensure products remain within a specific low-temperature range throughout the supply chain. The absence of continuous cold chain facilities is a major factor leading to significant postharvest losses in fruits and vegetables, impacting farmers' incomes and the economic contribution of the agricultural sector. Developing countries still have underdeveloped cold chain systems mainly due to insufficient investments in essential infrastructure and a lack of necessary management expertise.

16.3.2.1 Storage Structures

Human beings have stored crops for centuries and different societies developed varying methods and structures for storage. The stores can be grouped into traditional and mechanical storage structures.

16.3.2.1.1 Traditional Storage Methods

- **On-site Storage:** On-site storage involves postponing harvest until the crop is ready for market, especially common in certain tuber crops where the land is still occupied by the growing crop and cannot be replanted. However, this method poses risks of disease and pest infestation. Delayed harvest in crops like tapioca (cassava) can result in reduced quality and starch content, and exposure to very low temperatures can lead to chilling injury.
- **Clamp Storage:** Cassava and potatoes are often stored using clamp storage. This method involves laying straw on the floor in layers, piling the crop, covering it with straw, and then burying it under the soil after a few weeks. Approximately 75% of cassava stored using clamp storage retains its original weight after about a month.
- **Evaporative Cool Storage:** Evaporative coolers function based on the principle of water evaporation's latent heat, where water requires energy to change from liquid to gas. The process of water evaporation absorbs heat from the surrounding air, cooling the storage environment. The cooling efficiency depends on the initial humidity level and the effectiveness of the evaporative surface. Evaporative cooling systems are most effective in dry regions or during dry seasons when relative humidity is low. There are two methods of evaporative cooling: active and passive.
 - **Active Method:** In the active method, a fan is used to draw air into the storage structure. This method is more efficient but requires electric energy. Air passes through a wet pad before circulating around the vegetables, cooling to a few degrees above the wet bulb temperature of the ambient air.
 - **Passive Method:** The passive method relies on natural or prevailing winds for air circulation. Examples include the Zero Energy Cool Chamber (ZECC) and charcoal cooler.
- **Zero Energy Cool Chamber:** ZECC can be constructed using locally available materials like bricks, sand, wood, dry grass, gunny bags, bamboo, and twine. If the evaporative cooling chamber is not shaded, a cover must be provided to offer shade. The construction of ZECC is simple and cost-effective, making it a practical solution for storage in various regions. Possible improvements can be made in ZECC according to the available materials but make sure that those do not interfere with principle of evaporative cooling.

16.3.2.1.2 Mechanical Storage Structures

Refrigerated Storage

The fundamental concept of refrigeration is to extract heat from items requiring cooling. In mechanical refrigeration, refrigerated gas, such as ammonia or freon, expands to absorb heat from the surroundings. The compressed air then passes through tubes containing hot gases before being compressed again. This cycle, where the gas is liquefied and then expanded, allows for precise temperature control. Refrigeration enables long-term storage of fruits and vegetables while maintaining their safety. However, some produce, especially vegetables with low unit values, can be susceptible to damage from the cold temperatures. Continuous temperature monitoring is essential to extend the shelf life of fresh produce during storage. The overall costs of constructing and operating refrigerated systems can vary significantly based on local material costs, labor expenses, and electricity rates.

CoolBot™

CoolBot™ represents a relatively recent innovation in small-scale mechanical cooling technology (Kitinoja & Wilson, 2021). It is utilized to set up cool rooms for storing fresh horticultural produce and chilled food items. For a small cold room with a 3.5 kW (1 ton) refrigeration capacity and a standard refrigeration system, the cost is approximately US\$7000. CoolBot™ was developed by a US-based company (Store It Cold, LLC) to prevent ice formation that can impede airflow and halt the cooling process. It is a digital controller that can be easily installed without altering the air conditioner's existing management system. Currently, a commercial refrigeration system is significantly more expensive (around 80–90% more) than a 1-ton room air conditioner equipped with a CoolBot™ control system. Unlike traditional commercial refrigeration systems, this automated control system is designed to redirect any condensed moisture on the refrigeration coils back into the cool room air, reducing product moisture loss.

Solar-Powered Cold Rooms

Solar cold chain technology, which harnesses solar energy to power refrigeration systems, offers a sustainable and possible cost-effective solution to postharvest management challenges. This technology can maintain optimal temperatures, reduce postharvest losses, and extend the shelf life of perishable commodities, leading to higher incomes for farmers and better-quality products for consumers. The use of solar energy in refrigeration systems is particularly promising due to its environmental cleanliness and abundant natural availability. Additionally, low-grade solar and waste heat can drive solar-powered refrigeration systems, making them a green alternative to traditional cold production machines.

One of the successful initiatives The ColdHubs, developed by the Dresden Institute for Air and Refrigeration (ILK) and executed by the Smallholders Foundation in Nigeria, aims to resolve the challenge faced by value chain stakeholders who lack the resources and expertise to store produce postharvest and during handling from farm to consumer (Odeyemi & Ikegwuonu, 2021). This off-grid solar-powered cold storage solution in Nigeria, utilizing renewable energy for

refrigeration, proves beneficial in remote areas with limited or no access to electricity. A standard ColdHubs structure measures 10 m × 10 m × 7 m externally and can store 2 metric tonnes of perishable food, accommodating up to 150 stacked plastic boxes sized at 0.54 m × 0.36 m × 0.27 m. The cold room features 120 mm thick insulating panels in its walls to uphold low temperatures, integrating solar energy generation and compression-based cold production technologies. Solar panels on the cold room's roof generate energy, stored in high-capacity batteries to power the monoblock refrigeration units through an inverter. These panels produce approximately 5.7 kWh of energy. With a well-sealed door to retain cold air within the chambers, the chilling temperature inside the storage units can be adjusted between 5 and 15 °C. Designed to withstand harsh weather conditions typical in humid regions, ColdHubs effectively caters to both rural and urban populations by extending the shelf life of perishable food, enhancing access to nutrient-rich options, and specifically benefiting women overseeing operations and transactions at ColdHubs stations. It also contributes to increasing the annual income of smallholder farmers by an estimated 25%.

16.4 Quality and Food Safety Practices

The quality of fruits and vegetables is determined by the degree of excellence or superiority of the produce. It encompasses a range of attributes and characteristics that contribute value to the food item. Quality can vary based on the intended use of the produce, such as its suitability for shipping, market presentation, internal attributes, nutritional content, and taste. A producer may assess a certain cultivar of fruit or vegetable as high quality when it not only looks good and has few visible defects but also exhibits traits like disease resistance, high yields, low requirements for fertilizers and pesticides, a flexible harvest window, and suitability for shipping. Distributors and retailers often prioritize pleasing appearance as a key criterion since many customers make purchasing decisions based on how the produce looks. However, ensuring safety and good taste quality is crucial for securing repeat purchases from consumers.

16.4.1 Factors to Consider Ensuring Produce Quality

When evaluating the quality of produce, key factors typically taken into consideration include visual appearance, texture, flavor, nutritional content, and safety. The importance assigned to these factors varies depending on market demand and the intended use of the produce, whether for fresh consumption, processing, or other purposes. Visual quality can be influenced by various factors specific to each crop. Examples include sprouting in potato tubers, rooting in onion bulbs, curvature of asparagus spears, compactness of cauliflower and broccoli heads, and shriveling or

wilting of leafy vegetables. Mechanical damages like bruises, punctures, cuts, or cracks, as well as signs of physiological issues, such as chilling injury, sunburn, irregular ripening, and damage from pests and diseases, can significantly impact visual quality.

A firm texture is crucial for most horticultural products, as it affects both cooking quality and the ability to withstand transportation stresses. Soft fruits are challenging to transport over long distances without incurring losses. Harvesting produce at the appropriate commercial maturity level is essential to minimize losses and ensure high consumer acceptance. For climacteric fruits and vegetables like bananas and tomatoes that continue to ripen postharvest, harvesting slightly before reaching full commercial maturity is ideal. Flavor quality can vary widely based on factors that influence different customer preferences. Fresh fruits and vegetables are important sources of vitamins, minerals, and dietary fiber. Mishandling, such as physical damage, exposure to high temperatures, low humidity, chilling injury, or prolonged storage, can lead to a loss of flavor and nutrients, particularly vitamin C. Stakeholders in the food supply chain need to have access to quality analysis equipment and established protocols to maintain and ensure the quality of produce throughout the supply chain.

16.4.2 Safety in Horticulture Produce

Fresh horticultural produce is commonly consumed either fresh or with minimal processing. Ensuring the food safety of horticulture produce during postharvest and fresh-cut handling involves four primary prevention programs:

- Good Agricultural Practices (GAPs).
- Good Manufacturing Practices (GMPs).
- Sanitation Procedures.
- Hazard Analysis Critical Control Points (HACCP).

Maintaining proper sanitation practices throughout the supply chain is crucial to minimize the risk of contamination by harmful chemicals or microbes.

Pathogenic microbes that can be present in fresh horticultural produce pose the greatest health risk to consumers. The level of microbial contamination on produce can indicate poor handling practices, particularly related to temperature control. Contamination sources may include infected field workers, contaminated soil and irrigation water, the use of manure, or even customers at retail locations. The most effective approach to ensuring food safety and reducing hazards is through prevention of contamination. While fresh produce cannot be guaranteed to be free of pathogens, microbial testing may not always detect infections even if present.

Key Points to Consider in the Good Agricultural Practices (GAP)

Prioritizing the prevention of microbiological contamination in fresh produce over corrective actions after contamination occurs. Implementing GAPs in all

controllable areas by growers or packers to minimize microbial food safety risks in fresh produce without compromising the food supply or environment. Recognizing that any contact with fresh produce can potentially lead to contamination, with human or animal feces being a primary source of contamination for many food-borne pathogens. Emphasizing worker hygiene and sanitation practices during all stages from production to transport to reduce the risk of microbial contamination. Upholding accountability at all levels of the agricultural system, including farms, packing facilities, distribution centers, and transportation operations, to ensure a strong food safety policy. Acknowledging that the risk of contamination is influenced by the quality and source of water whenever it comes into contact with fresh produce.

16.5 Conclusions

In conclusion, the implementation of small-scale postharvest practices is essential for strengthening sustainability in the handling of horticulture crops. By adopting efficient and sustainable techniques, farmers can significantly reduce postharvest losses, improve product quality, and enhance the overall sustainability of their operations. These practices not only contribute to environmental conservation by minimizing waste and resource depletion but also promote economic viability for small-scale farmers. By focusing on practices such as proper handling, storage, and transportation methods, farmers can increase the shelf life of their produce, reduce spoilage, and access broader markets, ultimately leading to increased income and livelihood security. Furthermore, sustainable postharvest practices play a pivotal role in ensuring food security, particularly in the face of climate change and environmental challenges. By enhancing the resilience of horticulture crop handling, farmers can better adapt to changing conditions and mitigate the impacts of climate variability on their harvests. Overall, the integration of small-scale postharvest practices not only benefits individual farmers but also contributes to the broader goal of building a more sustainable and resilient agricultural sector. By prioritizing sustainability in the handling of horticulture crops, farmers can improve efficiency, profitability, and environmental stewardship, paving the way for a more sustainable future in agriculture.

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Chapter 17

Spatial Technologies for Sustainable Agriculture Using Global Information System, Global Positioning System, and Differential Global Positioning System in Climate Smart Crop System



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17.1 Introduction

The world is witnessing an exponential increase in the number of people around the globe. The growth in global population is leading to a rise in hunger putting an overall pressure on the farming sector of the world. The surge in demand for increasing crop production has put the farmers into taking steps to overall increase the farming production. Along with overpopulation, changes in the climatic conditions have also become very prevalent in current scenario which is causing a significant negative effect on agriculture and crop production. The over-exploitation of fossil fuels, deforestation, and urbanization are few of the reasons for such climatic instability (Crowley, 2000). These climatic changes causing sudden heavy rainfall leading to situations like heavy flood, extreme drought or abrupt change in weather damages the crop yield and affects the overall crop production (Pathak et al., 2024; Rind et al., 1989). The constant pressure to produce large amount of better-quality crops with highest yield has put the farmers into thinking especially in the developing and under-developed countries. To relieve this problem, it is important to upgrade the agricultural sector with modern technologies so that it is able to meet the rising demand for meal and food products (Seth & Misra, 2014). Such problems are mitigated by using of modern tools and technologies in agriculture. Mostly the developing countries tend to struggle with being updated with the latest technologies and tools for better farming practices (Bargali et al., 2024). Conventional

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farming that was once thought to be a relief for the farmers have turned out to produce under quality and quantity of crops due to the use of heavy synthetic fertilizers and pesticides making the crops dependent on outside sources of compound application leading to soil quality degradation, emission of harmful greenhouse gases, loss of biodiversity in the eco-system, water contamination, loss of knowledge of traditional farming practices, environmental degradation, and putting human health at high risk (Suwanmaneepong et al., 2020). In order to alleviate the quantity of crop production by the farmers in the developing nations, they must enhance their understanding about precision agricultural technologies to mitigate challenges with constantly-changing environmental condition and production challenges by maximizing their growth yield but minimizing any agricultural foreign inputs (Verma et al., 2024; Farid et al., 2023).

Precision agriculture was presented in the midway through the 1980s (Robert, 2002). It provides the farmers with modern technologies to maximize agricultural yield by maintaining the soil quality. This technology has been greatly adopted by the developed countries, but it yet needs to have a strong foundation in the developing and under-developed countries. They are usually not welcomed by such countries because of its unique land capturing properties, insufficient facilities and infrastructure, unwillingness of the farmers of the region to adapt using new technologies, and for various other social, economic, and ecological circumstances. Precision agriculture is also known as smart farming (Deichmann et al., 2016). Precision agricultural technology does not provide any financial profit to the farmers, but it helps them to choose an appropriate technological method to increase their crop productivity by maintaining a trust on the decisions given by the technological tools which indirectly provides the farmers with higher income. Modernized tracking of any yield variability by utilizing different technologies can help in better management of farming practices and respond better to the concern causing difference in yield productivity. With precision agriculture, data collection and analysis may be computerized for better accuracy and the ability to make the best possible decisions (Sharma & Srushtideep, 2022). Precision agriculture integrates new technologies that consists of remote sensing (RS), global information system (GIS), geographical positioning system (GPS), differential global positioning system (DGPS) are various tools of geospatial technologies (Mitran et al., 2021) that helps to increase the agricultural productivity by enhancing the measurement and evaluation of field variability by using sensors and ICT applications and increase the cost-benefit balance for the farmers (Brisco et al., 1998; Waqas et al., 2023). It helps to predict forthcoming weather changes, protect environment, and analyze the farm requirement in accordance to its requirement to prevent difficulties during farming and irrigation (Atwadkar & Patil, 2023). Remote sensing (RS) is a tool used in geospatial technologies which is scientific and uses sensors installed on satellites, drones, other aircrafts and sometimes on ground-based devices to collect and observe data such as aerial photographs, satellite images, etc. of crop and soil properties helping into making decisions on crop management and soil management (Tenkorang et al., 2008). GPS is one of the primary technologies that have made precision agriculture possible. Receivers of GPS get sufficient cost-effective precision activities, such as yield mapping, grid sampling, variable rate application, and

more which can be done with outmost accuracy (Tavanappanavar et al., 2024). Farmers can utilize GPS to locate agricultural data, such as weed invasion, pest distribution, and soil type (Sharma & Srushtideep, 2022). Another tool that is used for precision farming is GIS. GIS is a collection of software tools that uses map data to work with its own datasets that is, it can be used to work with data related to a particular place or a spatially defined area present on the globe to make certain decisions (Coppock, 1995). Field soil type, top and underground drainage, agriculture, rate of usage of chemically synthesized fertilizers and pesticides, crop yield can be seen in GIS tool dataset which is analyzed and understand the connections between all these components and various factors affecting a crop at a specific location (Maurya et al., 2024). DGPS provides accurate location data for agricultural farm machinery that includes tractors, harvesters that reduce waste production and maximize the use of resources by providing exact control. It favors site-specific management practices and can precisely measure and record crop yield in immediate time (Vetter, 1996). It provides the farmers with favorable tools and decisions about agriculture on the basis of its processed data and tracks the effect of worldwide agricultural rules and actions (Vajjiravel et al., 2024). This chapter deals with the details of different spatial technological tools used to modernize agricultural practices, their synergistic use with sustainable developmental farming to mitigate challenges caused by abrupt climatic changes and produce higher quantity of nutrition rich crops and crop products resulting into higher earnings for farmers and their futuristic approaches.

17.2 Negative Impact of Climate Stress on Agriculture

Agricultural sector in the world is very prone to rapid changes in the weather conditions (Anwar et al., 2012). Frequent climate changes have a negative impact on the irrigation yield and the health of the crops produced. It also damages the farms and makes them unsuitable for crop production. It also causes degradation of the nutrient content of the crops by contaminating the farm soil and irrigation water, and excessive moisture or dryness may cause the crops to lose its viability even after the crops are harvested. Farmers around the globe are concerned about the climate changes putting biotic and abiotic stresses on the farm causing a pressure on the farm yield and post-harvest losses. Rise in global temperature due to pollution has resulted in crop loss around the world (Lee et al., 2024). Unusual increase or decrease in rainfall, severe drought, cyclone, and other climatic stress are one of the main reasons that is one of the major concerns of the farmers and puts the farm at high risk of damage (Kumari et al., 2024). Spatial technologies are modern scientific tools that are adapted by the farmers to help them with coping up of climatic stress. Modern geospatial technologies help the farmers to provide beforehand information about any unnatural climatic stress, its frequency, direction, time span and help them to make suitable decisions about the farm to protect the crops and have higher irrigation rate and nutrition value of the harvested crops and also with protecting of the farm land and preventing financial and production loss of the farmer (Jin et al., 2024).

17.3 The Use of Digital Spatial Technologies for Sustainable Farming

Farming practices in developing countries are not enough modernized to combat surrounding stress conditions and increase the production of nutrient-rich crops simultaneously (Kim et al., 2024a, b) (Fig. 17.1). In addition to overpopulation, environmental challenges caused due to high or low heat temperatures, altered precipitation, increased carbondioxide emission, unusual flooding, drought, cyclones, and increased soil salinity are absolute nightmares for the poor farmers leading to an increase in production cost, pest, and disease outbreaks making it impossible to feed the hunger of about 9.7 billion people predicted by the year 2050 (Lobell & Gourdj, 2012; Mondéjar et al., 2021). Although the farmers of the developed countries are already using these fundamental tools, the farmers of the developing nation need to be introduced with the latest technologies and farming practices, to mitigate production losses and have high nutrition value yield (Hazaimh et al., 2024). Geography-related technology or geospatial technology provides the purpose to efficiently collect, store, update, alter, evaluate, and display geographically linked information helping the farmers to make profitable decisions and warning them by providing early hand information about any natural calamity (Mushtaq et al., 2024). It consists of a collection of computer hardwares, software, geographical information's and people using them (Mohyuddin et al., 2024). The technologies including GIS, GPS, GDPS and RS have been used extensively in farming since the beginning of 1990s (Raj et al., 2021). Farmers can measure the spatial arrangements and different timespans in soil, irrigation, and vegetation by taking the advantage of global navigation satellite system (GNSS) technology which can help to trace agricultural mechanism and improve the quality and availability of digital geographic information (Kumar et al., 2024a, b). GNSS technology is typically used in precision agriculture to collect visual guidance and autoguidance point data (Nowak,



Fig. 17.1 The use of geospatial tools and the correlation between its use, its role into making decisions that help the farmers and its effect on the increased production of crops

2021). Together these technologies help to provide accurate and profitable information to be used by the farmers to avoid any agricultural losses, is time-efficient, avoid the use of external components in the agricultural fields and prevent environment degradation. All these advantages make the use of geospatial technologies in agricultural field a good choice for the farmers (Deichmann et al., 2016).

17.4 The Simultaneous Effect of Sustainable Agriculture and Spatial Tools Usage on Farming

The simultaneous use of geospatial technologies and practice of sustainable agriculture to combat the challenges of environmental stress on the agricultural productivity is quite an innovative approach (Upadhyay et al., 2024). Precision agriculture being a part of smart agriculture helps to reduce the expenses and optimize returns, along with sustainable agriculture both acts as for global management perspective and being site-specific (Delgado et al., 2019). Using various geospatial technologies, farmers can accurately spot and monitor their fields using GIS and remote sensing tools helping the farmers to identify areas prone to various severe climatic conditions allowing the farmers to apply targeted adaptation strategies, monitor changes in their land, such as the percent of their land being used, amount of carbon in soil, concentration of salinity in soil, present of water-logging, etc. to take decisions about different sustainable agricultural practices such as needed afforestation (Sharma et al., 2022), site-specific application of external components mostly consisting of advantageous natural products and renewable resources withdrawn naturally from the farm itself, resulting into better crop production with high nutritional value by overcoming the effects of climate changes (Velten et al., 2015; Satapathy et al., 2008).

17.5 Different Types of Spatial Technologies Used in the Field of Cultivation

Discoveries and advancements made in technology and science during the twentieth and the twenty-first century, includes these spatial technologies, i.e., GIS, GPS, DGPS, have led the farmers to utilize farm equipment in order to enhance the yield of crop and to make it is sustainable (Fig. 17.2).

Spatial technologies play a pivotal role in making the sustainable farming the preferable method by showing its role in major agriculture applications like, soils, lands, crops, moisture content, weather, and any other threats that are related to agricultural data and study (Mitran et al., 2020). These spatial technologies play a meaningful role in agriculture such as smooth and timely data procurement, real-time analysis, high resolution and accurate mapping, betterment in crop yield and its productivity, easy broadcast of agricultural information through web, in-season crop damage estimation, and optimizing agricultural earnings while minimizing the risk (Kim et al., 2024a, b).

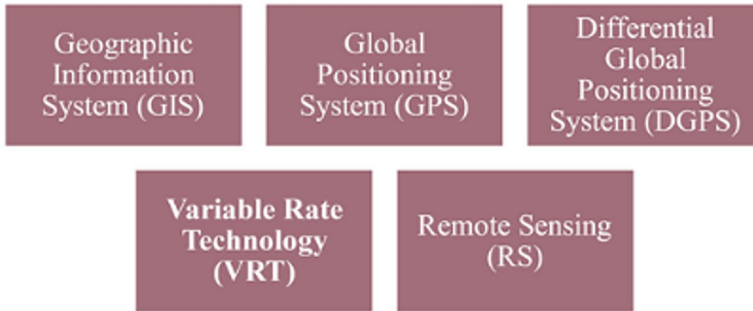


Fig. 17.2 Different types of spatial technologies that are used in agriculture

There are various approaches for better augmentation of sustainable agriculture through geospatial tools such as climate-smart agriculture (CSA), precision agriculture (PA), sustainable agriculture (SA), and others (Kumar et al., 2024c, d). These technologies can help in optimizing usage of field data and assets. It also helps to decrease the production price and farm income. To boost agricultural performance and environmental condition, precision farming (PF) involves using geospatial tools and methodologies to evaluate the temporal and geographical variability related to crop production parameters (Ram et al., 2024).

17.6 Role of Different Spatial Technologies in Agricultural System for Sustainable Farming

17.6.1 *Geographic Information System (GIS)*

GIS is considered as the brain of precise agriculture (PA) (Padhiary et al., 2024). GIS applications were first used in 1960. The geographic information system is an important constituent of the precision farming or precision agriculture system. Real-time data analysis generation becomes too difficult without using these spatial tools such as GIS, GPS, DGPS. Geographic information system (GIS) helps to fetch a lot of information which is necessary to make numerous precision agriculture related choices (Kumar et al., 2024a, b, c, d, e). GIS is essential for picking up and storing geospatial data since it has the capability to analyze even large amount of data. This is an important information which leads to weather forecasting, analyzing of production trends, conceptualizing the parameters of the field including runoff and outflow of the land, slope, topography, soil status, its moisture, and other chemical and physiological properties. A geographic information system (GIS) is an aggregation of computer hardware, software, storage, modeling or logical interface, operating staff, and geographic data gathered using remote sensing equipment or capturing devices. GISs can yield qualitatively different results than population in between species dynamic models (Soussi et al., 2024).

A database management system is built into GIS to manage two kinds of data: attribute data, which is an attribute of an object, and spatial data, which is georeferenced information from the real world. To identify trends, patterns, shapes, and linkages among the data, it is subjected to spatial analysis (Brar et al., 2024). There are several types of spatial analysis, one of them being overlay analysis, which involves placing over thematic layers to gain access into the data, proximity assessment, which measures as to how close resemblances are to one another, and buffer analysis, which uses the distance between features to identify areas inside or outside the buffer region (Choudhary et al., 2024).

17.6.2 Global Positioning System (GPS)

GPS as the name suggest, helps in fetching information about various geospatial data about the field as geographic analyzed data and determines the exact location regularly. The data acquired using of GPS is collected and kept in the geographic information system (GIS) that helps in their visualization using a computer to analyses and interpret spatial data and helps in the formation of digital maps of farm area or the field for creating management practices, (Fitzgerald et al., 2004). With nearly 24 satellites tracking the Earth at any given moment, the US Department of Defense's GPS is currently in use throughout the world. The latitude, longitude, and elevation of an item or a place can be obtained in 3D plain using the Navigation Satellite Timing and Range Global Positioning System, or NAVSTAR GPS. GPS applications have a vast role to perform in military, navigation, surveying, urban mapping, field sampling measurement, air traffic control, wildlife tracking, etc. (Kumar et al., 2024e). Yield maps are also produced by GPS receivers and yield monitors (Shannon et al., 2002).

Its application makes it so useful for maintaining the sustainable agriculture. Mapping of trees utilizes both the qualitative and quantitative data collection techniques to create database of spatial location and attributes information of the trees (Saharan et al., 2023). GPS is widely used for mapping fields, applying fertilizer, and tracking crop productivity. India's precision farming system has taken a new turn because to GPS technology and the growth of field applications (Yigit et al., 2025).

17.6.3 Differential Global Positioning System (DGPS)

It is another technology that improves the accuracy of GPS that is known to use pseudo range errors calculation that is done by other GPS receivers among the same geographic location (Fig. 17.3). The accuracy plays an important part in precision farming (PF), it demands for technologies like DGPS. A series of satellite is used to identify the address of farm that is in a short distance of the real field location



Fig. 17.3 Geospatial technologies that are used for precision farming, i.e., GIS, GPS, DGPS

Table 17.1 Summarizing various geospatial tools, their advantages, disadvantages, and application that are used in the agricultural field to combat climatic stress on the irrigation

Spatial tool	Advantage	Disadvantage	Application
Geographic information system (GIS)	Helps in topsoil evaluation.	The usage is little complex, it needs proper trained person to handle.	It is used for getting better agricultural judgments.
Global positioning system (GPS)	Regulates effective field utilization.	It requires proper training to the farmers beforehand, it is expensive.	It is a component in precision farming, evaluates the effectiveness of pest and disease preventive involvement.
Variable rate technology (VRT)	It is environmentally friendly. It also leads to better agricultural yield.	It is expensive to use.	It helps in precision application of external source of fertilizers or pesticides.
Remote sensing (RS)	It has a vast area coverage.	It is an expensive technology to be used.	It helps in the observation of crops for detection of any pests.
Differential global positioning system (DGPS)	It has better accuracy, better data coverage and has real-time analysis power.	It is expensive. It is complex to use.	It is applicable for monitoring for better crop health and helps in precision agriculture.

(Yang et al., 2020). The value of having precise knowledge of the location is very important for the sustainability of the agriculture. The knowledge of precise knowledge requires: Soil sample and laboratory outcome places can be analyzed to a soil map; pesticides and fertilizers that can showcase soil properties and also showcase soil quality that consist of soil drainage and relief (Table 17.1).

17.6.4 Variable Rate Technology (VRT)

The term variable rate technology (VRT) refers to agricultural plot essentials with the capacity to specifically restrain the amount of crop distribution of supplies (Mariyam et al., 2024). The application of common crops inputs such as tillage, fertilizer, nutrients, weedicide, pest control and plant population along with irrigation. Variable rate application (VRA) may range from simple rate flow control to more complicated rate, chemical mix, and application pattern management. VRT can also be used to deal with the spatial variability between distinct farm zones. Without variability, variable rate technologies (VRT) cannot be used as it is always present in farmer's field. Soil is obtained from a methodological mesh to form a map for every characteristic, which is also called mesh soil sampling. Such maps are imported for a variable rate application and works as the foundation of VRT. Depending on elements of the map, the computer and GPS accepts direct and refrain changes in the amount of product delivery or fertilizer product (Dhanaraju et al., 2022).

17.6.5 Remote Sensing (RS)

Remote sensing technology typically uses sensors or instruments installed on the devices such as a satellite, drones, or any other areal aircraft. The object emits or reflects certain electromagnetic radiations that is absorbed by the sensors or the instruments (Weiss et al., 2020). With the starting of aerial photography to identify soil resources in 1929, crop production and management in agriculture have gained a lot of advantage using spatial images. The connection between different crop metabolisms and crop characteristics is the basis of using such a geospatial tool. To model crop growth and crop production, few process by merging of spectrum data with meteorological information and crop growth parameters are considered which is divided into different important steps for remote sensing system (Kumar et al., 2021). They are regular coverage, fast information, rapid data delivery, integration of agricultural, meteorological data expert system, and spatial resolution between 5 and 22 m (Seelan et al., 2003; Jackson, 1984). RS helps in the identification of low level of essential nutrients, water content in soil, attack by pests, disease or weed on the crops (Tenkorang et al., 2008). RS has proved to be an efficient tool for tracking irrigated lands providing irrigated field overview in many wavelength regions at temporal frequencies that is sufficient for analyzing the maturity, development, and harvest of the crops (Özdoğan & Gutman, 2008; Thenkabail et al., 2005). Data collected over many years allows the comparison of images showing differences in them over the years. RS helps to combat climate changes since it can beforehand provide information about any future climatic threat and can provide suggestions according to the warnings to help the farmers in decision-making about the betterment and safety of the irrigated land (Brion & Balahadia, 2017).

Although the scope for using remote sensing technology in agricultural field profitably is huge and has a lot of potential, yet it is being accepted and used by smaller number of farmers around (Attri et al., 2025). Remote sensing technology is known to provide detailed and immediate information about environment and crop health, it is known to save time and is cost-efficient making it useful for monitoring irrigated land inventories in developing countries where the resources are not in sufficient amount and accurate data is hard to come by (Özdoğan et al., 2010). It helps in better production of crops and is precise and specific reducing the formation of waste and improving the overall crop health (Khanal et al., 2020). The drawback of this technology is that bad weather conditions can interfere with the vision of the ground from launching base that can lead to non-specific and interrupted data collection (Gnann et al., 2022). Other factors such as height and wavelength can also restrict the capabilities of remote sensing instruments. Bad weather conditions can cause late obtaining of crucial information because of restricted data acquiring (Rao et al., 2022). Although this technology has been frequently used for large-scale crop assessment and yield estimations but it is less common than other geospatial technologies such as GPS, GIS, and others (Seelan et al., 2003).

17.6.6 Sensors and Networks of Sensors for Agriculture Precursors

When integrating different PA technologies, dependable and reasonably priced real-time sensor systems are essential. Large volumes of field data may now be easily collected thanks to sensors; formerly, this would be a labor-intensive process that frequently requires laboratory equipment and analysis (Zhang et al., 2021). Various sensors have been used to analyze parameters such as moisture content, temperature, vegetation, consistency, structure, amount of nutrient present, vapor, and air (Sharma et al., 2024). According to the study of (Hakim et al., 2016), sensor data is used to keep a check on drought, soil, and plant conditions as well as identify crops species, identify stress situations, and locate and recognize pests and weeds.

17.7 Electrical Sensors, Electro-Chemical and Electro-Magnetic Sensors

The ability of a material to carry electricity can be evaluated using electrical sensors. Variations in the biophysical and biochemical qualities of the soil, which are measured in the form of fluctuating electric framework, have an impact on the behavior of electrical circuits. Due to their rapid counter time, cost-effective, and exceptional sustainability, electrical sensors are currently the most useful option for

mobile soil mapping (Sharma et al., 2020). The resulting soil maps are correlated with various properties of soil such as soil water content, humus, texture, and soil salt content (Adamchuk et al., 2004). Electrical sensors come in a variety of forms, including mechanical, electro-chemical, and electro-magnetic. Considering their rapid response time, cost efficiency, and exceptional durability, electrical sensors are currently the most accurate option for transferrable soil mapping. Such soil mapping is helpful for the farmers to understand the quality of the farm soil and act according to it in order to irrigate a greater number of crops with the highest nutritional value (Gupta et al., 2022).

Electro-chemical sensors use ion-channel selectivity, which produces electrically charged ion output in counter the activity of specific ions for example K^+ , H^+ , NO_3^- , and Na^+ , that are used to find these in the soil. Precision farming requires precise information on the pH and nutrient levels of the soil, which is what these sensors provide (Saleem et al., 2023). The reference electrode of this sensor keeps a constant voltage but the active electrode finds a specific target ion (Yin et al., 2021). Sensors installed on specialized sleds can be used to gather, process, and map data about the chemical composition of the soil. Many electro-chemical ion detectors use an ion-selective membrane (ISM) that is filled with ionophores (agents for lipophilic chelation) that only react with target ions as well as an electro-chemical apparatus that converts reactions into read out signals using potentiometry (Roy and Kalambukattu, 2020).

Many researchers have developed ion-channel selectivity converter for measuring soil pH, NO_3^- , K^+ , Ca^{2+} , Mg^{2+} , and PO_4^- . These electrodes can be used in precision agriculture to manage nutrients specific to a given site of the farm (Kim et al., 2024c; Xiao et al., 1995).

As the active electrode of this sensor finds a specific target ion, the reference electrode keeps the voltage constant. The pH of the soil affects how much should be added to improve the soil that is to be treated, such as acidic and alkaline type of soil (Rossel and Walter, 2003).

Electro-magnetic sensors are used to examine the magnetic behavior of different soil qualities, numerous measurement methodologies are employed because various types of soil attributes cannot be accurately predicted by a single parameter at the same time. (Choudhary et al., 2025) tried to investigate the soil's conductive and capacitive properties. Since the dielectric constant of aqua is a magnitude that is larger compared to soil, measuring electric capability or the dielectric constant is an important effective way to measure the water content of the soil (Agnihotri & Seth, 2016). A common electro-magnetic sensor gauges the water content of the soil by measuring its dielectric constant. To observe the soil moisture levels across a farm, electrical sensors can be used simultaneously with rain gauge stations (Chauhan et al., 2023). This technology is being highly recommended to be used by farmer in drought prone area and to measure the amount of drought intensity of that particular soil. Air flow sensors are the types of electro-magnetic sensors that are used for gauging many aspects of soil, i.e., complexion, structure, soil type, its structure, and water content (Agnihotri & Seth, 2017).

Electro-mechanical sensors are another type of sensors that are being used in various agriculture-based applications. It can evaluate the soil's mechanical preventiveness and compaction. These sensors use a long-extending probe into the ground to measure resistive forces using strain gauges or load cells. To measure the number of corn plants as they got closer to the obtaining chains of a combine header, (Sudduth et al., 2002) developed and assessed the electro-mechanical sensor. The sensors slightly underestimated the true population during harvest as compared to manual counts. When operating, the combine header should be at a distance of no more than 2 m or near to the ground (Gupta & Seth, 2021). Measurement of the capacitance or the dielectric constant is a precise process to analyze the water content of the soil, as the soil magnitude is greater than that of water magnitude (Ge et al., 2011).

Electrical sensors have the advantage of being able to measure soil variability fast and non-destructively, which takes it possible to precisely control and monitor soil nutrients. Real-time assessment of important soil biochemical and biophysical properties is a potential use for electrochemical, electro-mechanical methodologies, enhancing up to the point soil nutrient supervision and monitoring (Samanta et al., 2024). Electrical sensor fusion that might be helpful to concurrently quantify regional difference of important crop-soil properties beneath different growth conditions, although this is still up in the air.

17.8 The Effect on Environment Due to the Precision Farming

It has long been believed that environmental benefits will result from precision agriculture. A more targeted application of input results into lesser loss of fertilizers and pest controlling agents to the environment, lower usage of water, and reduced greenhouse gases emission such as methane, hydrogen, carbon dioxide, among other environmental benefits (Prajapati et al., 2022). But often, the extent of these effects is unclear or vastly unstable (Balafoutis et al., 2017; Johnson et al., 2007). Furthermore, rather than emphasizing actual effects, most of the research explores prospective implementations based on speculated readings or model forecast. Various studies show a link between the environmental performance of precision agriculture and its practical application in agriculture. Due to precision agriculture, the effect of greenhouse gas (GHG) emissions also lowered. The usage of fuel is decreased via machine guidance and supervised traffic farming since there is less turnover in agricultural operations. (Jensen et al., 2012) report a 25% reduction in fuel expenses, and (Shockley et al., 2011) claim that instruction systems can cut fuel usage up to 6%. These savings are higher and come with further advantages for large-scale fields, like less runoff, erosion, and compaction of the soil (Balafoutis et al., 2017). A reduction in nitrogen losses as NH_4^+ and NO is suggested by a drop

in effluents (Balafoutis et al., 2017). In a case study on German maize yield, VRT nitrogen treatment that results in a 34% reduction in nitrous oxide emissions (Xing & Wang, 2024).

17.9 Precision Farming over Traditional Farming

Precision farming is different from traditional farming and it is also considered to be a better initiative for a sustainable agriculture (Kumar & Seth., 2021). In precision farming, field is broken into distinctive zones, and the field is treated as heterogeneous, whereas in traditional farming, the whole field is approached where the field is treated as homogeneous. In precision farming, various spatial technological tools such as GIS, GPS, DGPS and other are used to manage the distinctive zones. In traditional farming, the inputs are applied on the field in a uniform manner across the whole field (Gupta & Seth., 2023). Precision farming not only saves a lot of time and effort but it also gives the real-time analysis to the farmers, whereas the traditional farming processes are time consuming and labor intensive. So, precision farming is better option for agricultural section to the farmers.

17.10 Future Prospective of Spatial Technology Used to Combat Climate Changes in Agriculture

Upgrading agricultural practices is a task in the developing countries (Zain et al., 2024). Awarding the farmers and the farm caretakes with different modern technologies and its benefits is a crucial step (Jindal & Seth, 2022). The farmers are needed to be given better training and explanation of the different spatial technologies that can be used by them for different benefits in the land. They should be trained about which technology to be used depending upon the situation, how to interpret their data and make conclusion according to the technology (Goel et al., 2021). The spatial technologies present should be updated to be more user-friendly for novice users. Along with being user-friendly, the technologies can be made more cheaper so that every farmer can be able to afford them and, the procedure of combining data from multiple sources to provide dataset can be improved to be better and effortless (Verma et al., 2023). The data available through the technological tools must be made more secure so that these sensitive information does not get misused by others. Also, the technological tools must be made more self-sufficient to be able to make decisions on its own without the need for information from any external sources (Duhan et al., 2017). There can be made improvements in already existing technologies that can predict adaptations to changing climatic conditions by providing of data on weather patterns, ground moisture and other information by the farmers (Blackmore et al., 2015).

17.11 Conclusion

Rise in population and hunger along with abrupt changes in the climatic conditions have led to a pressure on the agricultural sector of the world. To deal with such negative consequences, the farmers around the world must boost their crop production along with increasing the crop nutrient value in a short span of time. To tackle such consequences, latest technologies and tools are being used by the farmers that help them to provide them with wide knowledge about any climatic changes that is coming, information about soil and soil components, irrigation water, and nutrient content. These geospatial technologies help the farmers to provide with the latest farm related information and help them to make decisions for the betterment of their crop and farmland. Such technologies although is of great importance and is useful but they are quite costly to be able to afford by small farmers and farmers from developing and under-developed countries. Apart from being expensive, these technologies also need proper training to be fully understood by the user. These technologies although is of great importance but has few reliability issues since, they are not specific enough as the analyzed data provided by them is usually provided by external sources. Such drawbacks can be mitigated in the future by proper farmer training and also upgradation or invention of better user-friendly and low-cost technologies that will overall help and benefit the farmers and the population around the globe.

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Chapter 18

Climate-Intelligent Agriculture: Robotic and UAV Approaches for Resilient Crop Systems



Harsh Nagar and Rajendra Machavaram

18.1 Introduction

Technology plays a crucial role in modern agriculture, particularly in mitigating the challenges posed by climate change. As climate change poses a significant threat to the sustainability and productivity of the global agricultural sector, innovative and adaptive approaches are essential to enhancing crop system resilience and ensuring long-term agricultural sustainability.

Rising global temperatures, unpredictable precipitation patterns, and the increasing frequency and severity of extreme weather events—such as droughts, floods, and storms—are directly impacting crop growth cycles, soil health, and water availability (IPCC, 2014). These changes result in reduced agricultural yields and heightened vulnerability to pests and diseases (FAO, 2016). For example, the Intergovernmental Panel on Climate Change (IPCC) forecasts that crop yields could decrease by up to 25% in certain regions by 2050 due to climate change (IPCC, 2014).

Agricultural systems worldwide are feeling the strain. In regions like sub-Saharan Africa and South Asia, where agriculture is heavily reliant on rainfall, shifts in weather patterns have led to prolonged droughts and water shortages, significantly impacting food security (Gornall et al., 2010). Similarly, in temperate regions, unpredictable weather can disrupt planting and harvesting schedules, leading to financial instability for farmers (Challinor et al., 2014).

Given these profound challenges, the adoption of innovative and adaptive agricultural practices is crucial. Traditional farming methods, while historically effective, are often ill-equipped to handle the rapid and unpredictable changes induced by climate change. There is a growing consensus among scientists and

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policymakers that technological advancements in agriculture are essential for building resilient crop systems (Godfray et al., 2010).

Innovative approaches, such as precision agriculture, utilize advanced technologies to optimize resource use and enhance crop management. Precision agriculture employs data-driven techniques to manage field variability, ensuring that crops receive the exact amounts of water, nutrients, and protection needed at the appropriate times (Gebbers & Adamchuk, 2010). By adopting these methods, farmers can improve crop productivity, reduce environmental impact, and better adapt to changing climatic conditions.

Robotics and unmanned aerial vehicles (UAVs) are at the forefront of this technological revolution in agriculture. Robotics involves the use of automated machines to perform various agricultural tasks with high efficiency and accuracy. These tasks include planting, weeding, fertilizing, and harvesting (Pedersen et al., 2006). Robotics can operate continuously and precisely, reducing labor costs and minimizing human error. For example, autonomous tractors equipped with GPS and advanced sensors can plant crops in perfectly straight lines, optimizing land use and increasing yields (Blackmore et al., 2005).

UAVs, commonly known as drones, offer a unique advantage in monitoring and assessing crop health from the air. They can capture high-resolution images and gather multispectral data, providing valuable insights into crop conditions, soil health, and pest infestations (Zhang & Kovacs, 2012). This aerial perspective allows for early detection of issues that might not be visible from the ground, enabling timely and targeted interventions (Hunt et al., 2010). For instance, UAVs equipped with thermal cameras can identify water stress in crops before it becomes visually apparent, allowing farmers to adjust irrigation schedules accordingly (Hoffmann et al., 2016).

Sensors, satellite imagery, and UAV data can be integrated into sophisticated models that predict crop performance, optimize input use, and identify potential threats (Bongiovanni & Lowenberg-Deboer, 2004).

This information can be processed by data analytics tools to generate actionable insights, such as the identification of areas in a field that necessitate additional irrigation or the detection of early indications of pest infestations (Mulla, 2013). Historical and real-time data analysis can be conducted by machine learning algorithms to forecast future trends, thereby assisting farmers in the planning of their operations and the mitigation of risks (Shamshiri et al., 2018). This data-driven farming approach not only improves productivity but also strengthens the resilience and sustainability of agricultural systems.

Case studies provide tangible examples of how robotics and UAVs have been successfully implemented in various agricultural settings, showcasing their impact on crop yields, resource use efficiency, and resilience to climate change (Boursianis et al., 2020).

For instance, a case study in Spain demonstrated how UAVs equipped with multispectral cameras were used to monitor the health of vineyards. The data collected allowed farmers to identify areas affected by disease early and apply targeted treatments, resulting in healthier crops and higher yields (Berni et al., 2009, Tzounis

et al., 2017). Ensuring that these technologies are accessible and affordable for smallholder farmers is crucial for their widespread adoption.

Looking forward, this chapter calls for continued research and development in climate-intelligent agriculture. Future advancements in robotics and UAV technology, coupled with innovations in data analytics and machine learning, will further enhance the capabilities and applications of these technologies (Walter et al., 2017). By addressing current challenges and exploring new opportunities, the agricultural sector can better adapt to the changing climate and secure global food security.

In summary, the introduction of this chapter sets the stage for a comprehensive exploration of how robotics and UAVs can transform agriculture in the face of climate change. By highlighting the urgent need for innovative approaches and the potential of advanced technologies, the introduction provides a compelling context for the detailed discussions that follow. It underscores the importance of leveraging robotics and UAVs to build resilient and sustainable agricultural systems, contributing to the ongoing discourse on climate-intelligent agriculture.

18.2 Climate Change and Agriculture

Climate change is characterized by alterations in temperature, precipitation patterns, and the frequency and intensity of extreme weather events. These changes significantly affect agricultural productivity. For instance, increasing global temperatures can lead to heat stress, which adversely impacts crop growth and yield. Research indicates that staple crops such as wheat, rice, and maize may experience yield reductions of 6%, 3.2%, and 7.4%, respectively, for each degree Celsius rise in global mean temperature (Lobell et al., 2011) (Fig. 18.1).

Additionally, alterations in precipitation patterns, such as the onset and duration of rainy seasons, can exacerbate water scarcity or result in flooding, both of which are detrimental to agriculture. For instance, in regions such as the Sahel, the recurrence of droughts has had a significant impact on subsistence cultivation and food security due to unpredictable rainfall (IPCC, 2014). Conversely, soil erosion and nutrient discharge can result from an abundance of precipitation, which can further diminish crop productivity and soil fertility (FAO, 2016).

Climate change influences the distribution and lifecycle of parasites and diseases, creating additional challenges for agriculture. Increased humidity and warmer temperatures provide optimal conditions for various diseases and pests, leading to more frequent and severe infestations. For example, fluctuating climatic conditions in Africa have been linked to the proliferation of the fall armyworm (*Spodoptera frugiperda*), resulting in significant crop losses across the region (FAO, 2017).

Additionally, the migration of pests and diseases to new regions, where they were previously not found, poses a threat to local crops and biodiversity. Farmers are forced to increase the use of pesticides, which can have negative environmental and health impacts, and lead to pest resistance over time (Deutsch et al., 2018).

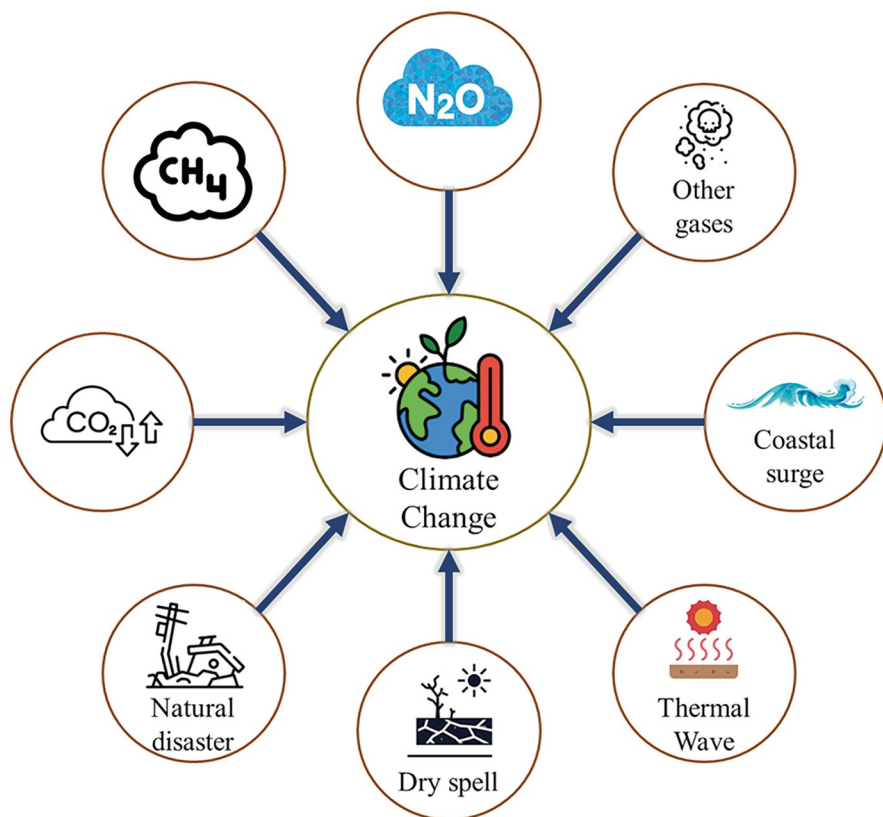


Fig. 18.1 Unveiling climate change: causal factors and impacts on agriculture and allied fields

18.2.1 Profound Effects of Climate Change on Crop Systems

Climate change contributes to soil degradation through various factors such as the loss of organic matter, desertification, and increased erosion. Extreme weather events like high winds and heavy rainfall accelerate soil erosion, depleting the nutrient-rich topsoil crucial for crop growth (Pimentel & Burgess, 2013). Desertification further diminishes the availability of arable land, particularly in regions like sub-Saharan Africa and Central Asia, exacerbated by unsustainable land management practices and prolonged droughts.

Soil organic matter, crucial for maintaining soil structure and fertility, is also at risk. (Lal, 2015). Water scarcity is another critical issue exacerbated by climate change. Many agricultural regions are already experiencing reduced water availability due to changing precipitation patterns, melting glaciers, and increased evaporation rates. In areas like the Western United States, prolonged droughts have led to severe water shortages, impacting irrigation and crop production (Diffenbaugh et al., 2015).

Irrigation systems, which are vital for maintaining crop yields in dry regions, are under strain as water resources become scarcer. Traditional irrigation methods often result in significant water wastage. Thus, there is a growing need for efficient water management practices, such as drip irrigation and the use of sensors to optimize water use (Postel et al., 2001).

The implications of climate change on the financial performance of producers are substantial. The financial resources of farmers are being strained by the increasing costs of inputs, such as pesticides, fertilizers, and water, as well as the lower crop yields. Smallholder farmers, who employ a significant portion of the global agricultural labor force, are particularly vulnerable due to their limited access to technology and currency (Morton, 2007).

Moreover, fluctuating market prices for agricultural products, driven by variable yields and changing demand patterns, create additional economic uncertainty. This financial instability can discourage investment in farming, leading to reduced productivity and increased poverty in rural areas (Porter et al., 2014).

To tackle these challenges, a variety of adaptation strategies are being investigated and put into practice. These strategies encompass the development and deployment of climate-resilient crop varieties, enhanced water management practices, and the adoption of sustainable land management techniques. Crop breeding programs are concentrating on creating varieties that exhibit tolerance to drought, resistance to heat, and resilience against pests (Palm et al., 2014a, b).

These adaptation strategies are significantly bolstered by technology. Farmers are now able to more effectively monitor and manage their crops as a result of advancements in biotechnology, remote sensing, and data analytics. For example, genetically modified crops that are resistant to pests and drought present substantial potential for increasing yields in difficult climatic conditions (Qaim, 2009; Mulla, 2013; Shamshiri et al., 2018).

18.3 Role of Robotics in Agriculture

As climate change imposes new challenges on farming, robotics offers innovative solutions to enhance productivity, efficiency, and sustainability. This section explores the various applications of robotics in agriculture, highlighting their potential to revolutionize crop management and cultivation.

Overview of Agricultural Robotics

Agricultural robotics encompasses a broad range of technologies designed to automate and optimize farming tasks. These robotic systems are capable of accurately and efficiently completing difficult jobs because they are outfitted with sophisticated sensors, artificial intelligence, and machine learning algorithms.

18.3.1 Applications of Robotic Technologies in Crop Management and Cultivation

1. Autonomous Field Robots:

- Autonomous tractors and field robots are designed to carry out operations like planting, weeding, and harvesting with the least amount of human assistance.
- These robots use GPS and machine vision to navigate fields, ensuring precise operations and reducing labor costs.
- Example: John Deere's autonomous tractor is equipped with cameras, radar, and GPS to operate without a driver, enhancing efficiency in large-scale farming.

2. Robotic Harvesting Systems:

- Robotic harvesters are developed to pick fruits and vegetables with care, minimizing damage and maximizing yield.
- These robots use computer vision and AI to identify ripe produce and execute delicate picking actions.
- Example: The SWEEPER robot, designed for harvesting sweet peppers, uses 3D vision and a gripper to accurately locate and pick fruits (Bac et al., [2014](#)).

3. Weed Control Robots:

- Autonomous weed control robots identify and eliminate weeds using mechanical, thermal, or chemical methods.
- These robots reduce the need for herbicides, promoting sustainable farming practices.
- Example: The Oz weeding robot navigates crop rows autonomously, using mechanical tools to remove weeds without harming crops.

4. Robotic Planting Systems:

- Robotic planters precisely place seeds in the soil at optimal depths and spacings, ensuring uniform germination and growth.
- These systems can adapt to varying soil conditions and optimize planting patterns.
- Example: The Fendt Xaver robotic planting system uses swarm technology, with multiple small robots working together to plant seeds efficiently.

5. Robotic Irrigation Systems:

- Robotic irrigation systems monitor soil moisture levels and adjust water delivery based on crop needs.
- These systems enhance water use efficiency, critical in regions facing water scarcity.

- Example: The Hortibot robot automates irrigation tasks to guarantee that crops receive the appropriate volume of water at the appropriate time (Pedersen et al., 2006).

6. *Crop Monitoring and Management:*

- In real time, robotic devices that are fitted with sensors and cameras monitor the health of crops, the conditions of the soil, and the presence of insect infestations.
- Data collected by these robots enable precise interventions, such as targeted pesticide application or nutrient management.
- Example: The BoniRob robot examines the development and condition of plants, offering farmers vital information to make well-informed decisions (Shamshiri et al., 2018).

Benefits of Robotic Technologies in Agriculture

- **Increased Efficiency:** Robotic systems perform repetitive and labor-intensive tasks quickly and accurately, increasing overall farm efficiency.
- **Reduced Labor Costs:** Automation reduces the reliance on manual labor, addressing labor shortages and lowering operational costs.
- **Precision Agriculture:** Robots enable precise application of inputs like seeds, fertilizers, and water, optimizing resource use and reducing waste.
- **Sustainability:** By minimizing the use of chemicals and improving resource efficiency, robotic technologies promote sustainable farming practices.
- **Enhanced Data Collection:** Robotic systems gather extensive data on the health of crops, conditions of the soil, and many environmental aspects, which aids in making decisions based on data.

Case Studies of Robotic Implementations

1. *Robotic Strawberry Harvesting:*

- The Octinion Rubion robot is designed to harvest strawberries autonomously, using soft grippers and 3D vision to pick ripe berries without causing damage (Van Henten et al., 2002).
- This robot enhances harvesting efficiency and reduces the reliance on seasonal labor.

2. *Autonomous Vineyard Management (continued):*

- The VineRobot project has pioneered an autonomous robot designed for vineyard monitoring, featuring sensors that assess soil properties, plant vigor, and grape quality.
- This technology enables vintners to make informed decisions regarding irrigation, fertilization, and harvest timing, thereby enhancing both grape quality and yield.

Challenges and Limitations of Agricultural Robotics

While robotics holds great promise for agriculture, several challenges and limitations must be addressed to realize its full potential.

- **High Initial Costs:** The development and deployment of robotic systems require significant financial investment, which can be a barrier for small- and medium-sized farms (Bechar & Vigneault, 2016).
- **Technical Complexity:** The integration of advanced technologies such as AI, machine learning, and computer vision requires technical expertise and continuous maintenance (Shamshiri et al., 2018).
- **Regulatory Hurdles:** The adoption of autonomous systems in agriculture is subject to regulatory approval and compliance with safety standards, which can vary by region (Wolfert et al., 2017).
- **Data Security and Privacy:** The usage of data-driven robotic systems raises concerns about data security and privacy, particularly regarding ownership and management of agricultural data (Kamilaris et al., 2017).

Future Directions in Agricultural Robotics

The future of agricultural robotics is poised for rapid advancements, driven by ongoing research and technological innovations.

- **Integration with IoT:** Combining robotic systems with the Internet of Things (IoT) will enable real-time communication and data sharing between various farm devices, enhancing overall farm management.
- **Advancements in AI:** Robots will become more independent and adaptive as a result of ongoing developments in artificial intelligence and machine learning, which will enhance their capacity for making decisions (Liakos et al., 2018).
- **Collaborative Robots (Cobots):** The creation of cobots (collaborative robots) that are intended to assist human laborers would improve farming operations' productivity and security (Villani et al., 2018).
- **Bio-inspired Robotics:** Research into bio-inspired robotics, which mimics the movement and behavior of animals and insects, will lead to more versatile and adaptable robotic systems.

18.4 Role of UAVs in Agriculture

UAVs, commonly referred to as drones, provide innovative solutions for crop monitoring, assessment, and management, especially in the realm of climate-intelligent agriculture. This section explores the wide-ranging applications of UAVs, their benefits, and the challenges inherent in their utilization.

Overview of UAV Technology in Agriculture

Unmanned aerial vehicles (UAVs) are capable of gathering real-time data and high-resolution aerial imagery because to their advanced sensors, cameras, and data

processing capabilities. These airborne vehicles provide valuable observations on the state of crops and fields and may be quickly and efficiently deployed over large areas.

18.4.1 Capabilities of UAVs in Crop Monitoring and Assessment

1. Crop Monitoring and Health Assessment

- Using multispectral and hyperspectral cameras, unmanned aerial vehicles (UAVs) may provide precise photos of crops, providing insights into factors such as disease prevalence, nutrient deficiencies, and plant health.
- These images help farmers detect issues early and implement targeted interventions, improving crop yield and quality.
- Data Reference: A study by Zhang and Kovacs (2012) demonstrated that UAV-based multispectral imaging could accurately detect nutrient deficiencies in wheat, allowing for timely corrective measures.

2. Field Mapping and Analysis

- UAVs generate high-resolution maps of agricultural fields, including elevation models and vegetation indices, which are essential for precision agriculture.
- These maps assist in identifying variations in soil properties, water distribution, and crop performance.
- Data Reference: Turner et al. (2011) used UAVs to create detailed vegetation index maps, this contributed to the 20% improvement in agricultural yield by optimizing fertilizer and irrigation.

3. Irrigation Management

- UAVs equipped with thermal sensors can monitor soil moisture levels and identify areas requiring irrigation, promoting efficient water use.
- These systems support precision irrigation, reducing water wastage and enhancing crop health.
- Data Reference: A study by Sishodia et al. (2020) found that UAV-based thermal imaging reduced water use by 15% while maintaining optimal crop growth in vineyards.

4. Pest and Disease Detection

- UAVs can identify early signs of pest infestations and diseases through high-resolution imagery and pattern recognition algorithms.
- Early detection allows for prompt response, which lowers crop losses and uses fewer pesticides.

- **Data Reference:** Huang et al. (2010) used UAVs to detect early stages of pest infestation in rice fields, resulting in a 30% reduction in pesticide use.

5. *Precision Spraying*

- UAVs equipped with spraying systems can deliver pesticides, herbicides, and fertilizers precisely where needed, minimizing chemical usage and environmental impact.
- These drones can navigate challenging terrain and reach areas that are difficult for ground-based machinery.

6. *Yield Estimation*

- UAVs can be used to estimate crop yield by analyzing crop density, plant height, and biomass using advanced imaging techniques.
- **Data Reference:** Hunt et al. (2010) showed that UAV-based imagery could predict corn yield with an accuracy of 85%, aiding in better harvest planning.

18.4.2 *Importance of Real-Time, High-Resolution Data for Decision-Making*

18.4.2.1 *Benefits of UAV Technologies in Agriculture*

- **Enhanced Data Collection:** UAVs offer real-time, high-resolution data that is essential for making well-informed decisions.
- **Cost-Effective Monitoring:** UAVs reduce the need for manual field inspections, saving time and labor costs.
- **Improved Resource Efficiency:** Precision agriculture techniques enabled by UAVs optimize the use of water, fertilizers, and pesticides.
- **Early Problem Detection:** UAVs help identify issues early, allowing for timely interventions that improve crop health and yield.
- **Scalability:** UAVs can be used on farms of all sizes, from small holdings to large commercial operations.

Challenges and Limitations of UAVs in Agriculture

While UAVs offer numerous benefits, several challenges must be addressed for their widespread adoption in agriculture.

- **Regulatory Constraints:** UAV operations are subject to regulations regarding flight permissions, altitude limits, and data privacy, which can vary by country (Bendre et al., 2015).
- **Technical Expertise:** Effective use of UAVs requires technical knowledge in operating drones, processing data, and interpreting imagery (Tsouros et al., 2019).
- **Data Management:** Managing and analyzing the vast amounts of data collected by UAVs can be challenging without appropriate tools and infrastructure.

Future Directions in UAV Technology for Agriculture

Constant innovation is expected to increase the capabilities and broaden the applications of UAV technology in agriculture, which bodes well for their future.

- **Integration with AI and Machine Learning:** According to Chlingaryan et al. (2018), the precision of crop monitoring and predictive analytics can be enhanced by integrating UAV data with AI algorithms.
- **Development of Swarm UAVs:** Swarm technology, where multiple drones work collaboratively, will increase efficiency and coverage area.
- **Enhanced Autonomy:** Advances in autonomous navigation and obstacle avoidance will enable UAVs to operate with minimal human intervention (Mogili & Deepak, 2018).
- **Improved Sensors:** Continued development of lightweight, high-resolution sensors will enhance the quality of data collected by UAVs.

18.5 Integration of Robotics and UAVs

This section explores the synergistic integration of robotics and UAV technology to optimize agricultural practices. The combination of these technologies presents unparalleled prospects for precision agriculture, facilitating enhanced efficiency and sustainability.

18.5.1 Synergies Between Robotics and UAVs

Combining robotics and UAVs provide comprehensive solutions for various agricultural challenges.

1. *Complementary Capabilities:*

- Robots have exceptional proficiency in executing operations at ground level, such as planting, weeding, and harvesting. They provide accuracy and uniformity in their performance.
- Unmanned airborne vehicles (UAVs) offer airborne viewpoints, capturing detailed images and up-to-date information for extensive monitoring and evaluation purposes.
- The integration of these technologies allows for a holistic approach to crop management, covering both macro- and micro-levels.

2. *Data Integration and Analysis:*

- Data collected by UAVs (e.g., aerial imagery, multispectral data) can be combined with ground-level data from robots (e.g., soil moisture, plant health metrics).

- Farmers will be able to gain insights that they can integrate into their operations by processing the combined data using powerful data analytics and machine learning algorithms.
- This synergy facilitates more accurate predictions and decision-making, enhancing crop yield and reducing resource wastage.

18.5.2 Enhanced Efficiency and Effectiveness in Climate-Intelligent Agriculture

The integration of robotics and UAVs enhances the efficiency and precision of agricultural operations, leading to several key benefits.

1. Precision Agriculture:

- Precision input application (e.g., water, fertilizers, and pesticides) is made possible by robotics and UAVs, which optimizes their use and minimizes environmental impact.
- This precision reduces input costs and promotes sustainable farming practices.

2. Improved Crop Health Monitoring:

- UAVs can quickly identify areas of concern (e.g., pest infestations, nutrient deficiencies) from an aerial view.
- Ground robots can then be deployed to those specific areas for targeted interventions, improving overall crop health.

3. Efficient Resource Management:

- Water, fertilizer, and human labor can all be better managed with the help of unmanned aerial vehicles (UAVs) and robots.
- For instance, UAVs can identify dry areas in a field, and robots can be directed to those areas for irrigation.

Experiments in Practice and Practical Uses

There are clear advantages to using UAVs and robotics in agriculture, as shown by real-world instances.

1. Vineyard Management:

- In a vineyard, UAVs are used to map the terrain and monitor vine health, while robots handle tasks like pruning and harvesting.
- This integration has resulted in increased grape yield and reduced labor costs.

2. Rice Farming:

- UAVs equipped with multispectral cameras monitor rice fields for signs of stress or disease, and robots are deployed to apply precise treatments.

- This approach has led to a 15% increase in rice yield and a significant reduction in pesticide use.

Challenges and Considerations

While the integration of robotics and UAVs offers numerous benefits, several challenges must be addressed.

1. *Technical Integration:*

- Ensuring seamless communication and data exchange between UAVs and robots requires robust technological frameworks and standards.
- Interoperability issues may arise due to different manufacturers and proprietary systems.

2. *Cost and Accessibility:*

- The initial investment in both UAV and robotic technologies can be high, potentially limiting their adoption by small-scale farmers.
- Strategies to reduce costs and increase accessibility, such as shared ownership models, are needed to promote widespread adoption.

Future Prospects

The future of integrated robotics and UAVs in agriculture is promising, with several advancements on the horizon.

1. *Autonomous Systems:*

- One of the main areas of research is the creation of fully autonomous systems, in which robots and UAVs function with little assistance from humans.
- Advances in artificial intelligence and machine learning will drive these developments, enhancing the efficiency and reliability of agricultural operations.

2. *Enhanced Data Analytics:*

- Improved data analytics tools will enable more sophisticated analysis of integrated data from UAVs and robots.
- Improved decision-making will be facilitated by these instruments' enhanced ability to reveal information about crop health, soil conditions, and environmental factors.

Combining robotics and UAVs in climate-smart agriculture provides a potent method for improving the durability and eco-friendliness of crop systems. By synergistically using the capabilities of both technologies, farmers can attain enhanced precision, efficiency, and adaptability in their agricultural methodologies. Despite the existence of hurdles, continuous research and technological breakthroughs hold the potential to fully utilize these integrated systems.

18.6 Precision Agriculture and Data Analytics

Precision agriculture leverages data and analytics to optimize farming operations, reduce waste, and improve crop yield and quality. This section explores how data-driven decision-making processes are revolutionizing agriculture and contributing to climate-intelligent practices.

18.6.1 *Role of Advanced Technologies in Precise, Data-Driven Decision-Making Processes*

Making precise, data-driven decisions in precision agriculture depends critically on the integration of cutting-edge technologies like IoT devices, remote sensing, and data analytics. Large-scale data is gathered, processed, and analyzed by these technologies, which yield useful insights that assist farmers improve their operations.

18.6.1.1 Internet of Things (IoT) in Agriculture

The term “Internet of Things” (IoT) refers to a system of linked computing devices that can instantly collect and share data. Internet of Things (IoT) gadgets in farming include automated machinery, GPS systems, and sensors that allow for precise data collection and monitoring.

1. **Soil Moisture Sensors:** These devices allow farmers to save water and make better irrigation schedules by measuring the soil’s moisture content. Reduce water waste and improve crop health by irrigating only when absolutely required.
2. **Weather Stations:** Data on humidity, precipitation, wind speed, and temperature is provided by Internet of Things (IoT) weather stations in real-time. By using this knowledge, agricultural practitioners can better protect crops from bad weather, determine the best times to plant and harvest, and more.

18.6.1.2 Remote Sensing and Satellite Imagery

Remote sensing technologies offer comprehensive data on crop health, soil conditions, and field variability. Examples of these technologies include satellite images and UAV-based multispectral imaging.

1. **Multispectral Imaging:** UAVs equipped with multispectral cameras capture images in various wavelengths, allowing for the detection of plant stress, nutrient deficiencies, and pest infestations. These images enable early intervention, reducing crop losses and improving yield.

2. **Conventional Vegetation Index (NDVI):** NDVI is a key metric derived from remote sensing data that indicates vegetation health. By analyzing NDVI maps, farmers can identify areas of poor plant health and take corrective actions.

18.6.1.3 Information Analysis and Artificial Intelligence

Predictive Analytics Based on past and current data, machine learning algorithms can forecast agricultural yields, pest outbreaks, and the best times to sow. These predictions help farmers plan their operations more effectively and reduce risks.

Precision Fertilization Data analytics can determine the precise amount of fertilizers needed for different areas of a field. This targeted approach minimizes fertilizer use, reduces costs, and mitigates environmental impact.

Benefits of Precision Agriculture and Data Analytics

1. **Resource Optimization:** Water, fertilizer, and pesticides can be used more efficiently with precision agriculture techniques. This lessens the financial burden on farmers while also reducing their negative effects on the environment.
2. **Sustainability:** Data analytics may help farmers improve agricultural output and quality by giving them a bird's-eye view of field conditions and crop health, so they can make educated decisions.

Challenges and Considerations

While precision agriculture and data analytics offer significant benefits, several challenges need to be addressed.

1. **Data Management:** It can be difficult to manage and analyze the massive amounts of data that IoT devices and remote sensing technologies create. To obtain useful insights, efficient data management systems and analytics tools are necessary.
2. **Cost and Accessibility:** Small-scale farmers may face significant upfront costs when investing in new technologies and data analytics infrastructure. Efficient cost reduction and improved accessibility strategies are necessary to encourage wider usage.
3. **Technical Expertise:** Effective use of precision agriculture technologies requires technical knowledge in operating devices, processing data, and interpreting results. Training and support are crucial for farmers to fully benefit from these technologies.

Integrating state-of-the-art technology with precision agriculture and data analytics allows for precise, data-driven decision-making, which is revolutionizing farming processes. Through the use of IoT devices, remote sensing, and machine learning, farmers have the opportunity to improve agricultural yields, maximize resource consumption, and push for sustainable agriculture. Resolving challenges

with data administration, cost, and technological know-how is crucial for fully utilizing precision agriculture to improve climate-smart practices.

18.7 Case Studies

This section of this chapter provides real-world examples of successful implementations of climate-intelligent agricultural practices.

18.7.1 *Real-World Examples of Successful Implementations*

Under this section, you will find case studies of various crops and regions that show how the use of modern technology has increased agricultural sustainability and productivity.

18.7.1.1 Autonomous Weeding Robots in Vegetable Farming

Autonomous weeding robots have been effectively utilized in vegetable production in California to tackle labor shortages and decrease the dependence on herbicides (Slaughter et al., 2008).

Benefits

- Autonomous robots can work nonstop, eliminating the need for human workers and thereby lowering labor expenses.
- Decreased herbicide use: Precision weeding reduces the need for chemical herbicides, promoting environmental sustainability.
- Increased crop yields: Efficient weed management results in healthier crops and higher yields.

18.7.1.2 UAV-Based Crop Monitoring in Rice Cultivation

UAVs outfitted with multispectral sensors have been used in Japan to monitor rice crops. The unmanned aerial vehicles (UAVs) acquire photographs of high resolution, which are then evaluated to evaluate the condition of crops, identify any lack of nutrients, and detect the presence of pest infestations.

Benefits

- UAVs provide timely data, allowing farmers to address problems before they escalate.
- Enhanced monitoring helps optimize crop growth and improve yields.

18.7.2 Impact on Diverse Crops and Varying Climates

This subsection explores the impact of climate-intelligent agricultural practices on different crops and climates, illustrating the adaptability and effectiveness of advanced technologies.

18.7.2.1 Precision Irrigation in Vineyard Management

In Spain, precision irrigation systems have been implemented in vineyards to address water scarcity and improve grape quality. This approach has led to significant water savings and improved grape yield and quality.

Impact

- **Water conservation:** Precision irrigation reduces water usage by delivering water only when and where it is needed.
- **Improved grape quality:** Maintaining consistent soil moisture levels enhances the quality of grapes, leading to increased market value.
- **Adaptability to climate variability:** Real-time data allows for adjustments in irrigation practices based on changing weather conditions.

18.7.2.2 Climate-Resilient Crop Management in Sub-Saharan Africa

Climate-resilient crop management techniques have been used in sub-Saharan Africa in response to the problems presented by climate change. These methods include conservation agriculture, the adoption of crop types resistant to drought, and the incorporation of digital tools for crop monitoring and weather forecasts.

Impact

- **Increased resilience:** Drought-tolerant varieties and conservation practices help crops withstand extreme weather conditions.
- **Improved food security:** Enhanced crop management practices lead to higher yields and more stable food supplies.
- **Sustainable farming:** Adoption of conservation agriculture promotes soil health and reduces environmental degradation.

The case studies presented in this section illustrate the implementation autonomous weeding robots in vegetable farming to UAV-based crop monitoring in rice cultivation, these real-world examples highlight the tangible benefits of climate-intelligent practices. Furthermore, the impact on diverse crops and varying climates demonstrates the adaptability and effectiveness of these technologies in promoting sustainable and resilient agricultural systems.

18.8 Resilient Crop Systems

In this section, we will explore the use of agricultural systems that are resilient and in light of the fact that weather patterns and environmental conditions are becoming more unpredictable, these measures are crucial for guaranteeing food sustainability and security.

18.8.1 *Strategies for Developing Agriculture Resilient to Climate Variability*

Developing resilient crop systems involves a multifaceted approach that includes the adoption of advanced technologies, the selection of climate-resilient crop varieties, and the implementation of sustainable farming practices. This subsection outlines several key strategies for enhancing the resilience of agricultural systems.

18.8.1.1 Adoption of Climate-Resilient Crop Varieties

An optimal approach to enhance resilience in agriculture involves the creation and implementation of crop cultivars that possess the ability to withstand and endure severe climatic circumstances, such as drought, heat waves, and floods.

- ***Drought-Tolerant Varieties:*** Crops bred for drought tolerance can maintain productivity under water-scarce conditions, ensuring stable yields even during dry spells (Araus & Cairns, 2014).
- ***Heat-Tolerant Varieties:*** Heat-tolerant crops are essential for regions experiencing rising temperatures. These varieties can withstand higher temperatures without a significant loss in yield (Tesfaye et al., 2017).
- ***Flood-Resistant Varieties:*** In areas prone to flooding, the development of flood-resistant crop varieties can prevent crop losses and ensure food security.

18.8.1.2 Sustainable Farming Practices

The implementation of sustainable agricultural practices is crucial in augmenting the resilience of crop systems. Integrated pest management, agroforestry, and conservation agriculture are some of these techniques.

- ***Conservation Agriculture:*** This method includes crop rotation, preserving soil cover, and causing as little disturbance to the land as possible. It makes crops more robust to climate unpredictability by enhancing soil health, decreasing erosion, and improving water retention (Palm et al., 2014a, b).

- **Agroforestry:** There are several advantages to incorporating trees into agricultural landscapes, such as greater carbon sequestration, higher biodiversity, and improved soil fertility. Agroforestry systems give farmers alternative revenue streams and are more adaptable to adverse weather occurrences (Garrity, 2004).

18.8.1.3 Use of Advanced Technologies

Building crop systems that can withstand changing weather conditions requires cutting-edge technology like the internet of things (IoT), remote sensing, and data analytics.

- **Data Analytics and Machine Learning:** Large-scale data analysis is done by these technologies to forecast agricultural performance, insect outbreaks, and weather trends. With the use of predictive analytics, farmers are better able to plan ahead and take proactive steps to safeguard their crops.

18.8.1.4 Diversification of Cropping Systems

Crop failure can be mitigated by increasing crop diversity in response to climate change. Crop diversification enhances ecosystem services, improves soil health, and provides multiple sources of income for farmers.

- Growing multiple crops in close proximity to one another improves resource use, lessens the impact of pests and diseases, and strengthens the resilience of farms as a whole (Lithourgidis et al., 2011).
- Crop Rotation: Crop failure resulting from unfavorable weather circumstances is decreased, soil fertility is enhanced, and insect and disease cycles are disrupted through the sequential planting of different crops (Davis et al., 2012).

18.8.1.5 Planning for the Efficient Use of Water

Particularly in areas where water is scarce, resilient agriculture requires efficient water management.

- **Rainwater Harvesting:** The act of gathering and preserving rainwater for the purpose of using it in agriculture can offer a dependable water supply in times of drought. Implementing this method decreases reliance on underground water sources and improves the amount of water accessible for agricultural purposes (Rockström et al., 2010).

In order to construct agriculture systems that can withstand the effects of climate change, it is necessary to employ a holistic approach that includes state-of-the-art technology, sustainable farming practices, climate-resilient crop varieties, and effective water management strategies (Feres & Soriano, 2007). Through the

implementation of these tactics, farmers can fortify their agricultural systems against climate fluctuations, guaranteeing steady and enduring food supply despite evolving environmental circumstances.

18.9 Sustainable Practices

The ninth section, “Sustainable Practices,” underscores the significance of adopting sustainable agricultural practices to ensure long-term resilience. It also explores the pivotal role of robotics and UAVs in enhancing sustainability within agricultural systems.

18.9.1 *Importance of Sustainable Practices for Long-Term Resilience*

Agricultural ecosystems rely on sustainable practices to ensure their long-term health and productivity. Not only can these methods aid in reducing the negative impacts of climate change, but they also encourage resource conservation, soil health, and biodiversity. Key sustainable practices include:

- **Soil Conservation:** Long-term soil productivity is ensured by methods like cover crops, decreased tillage, and organic amendments that improve soil structure, fertility, and water retention (Lal, 2015).
- **Water Management:** Efficient irrigation methods like drip irrigation and rainwater harvesting minimize water use and enhance water availability during dry periods (Feres & Soriano, 2007).
- **Biodiversity Conservation:** Crop rotation, intercropping, and the use of native plant species increase biodiversity, which supports ecosystem services and pest management (Altieri, 1999).

18.9.2 *Role of Robotics and UAVs in Achieving Sustainability*

Sustainable agriculture is made possible with the use of robotics and UAVs because of the accurate, data-driven solutions they provide for optimizing resource utilization and reducing environmental impact.

1. **Precision Application:** Gebbers and Adamchuk (2010) state that robots with sensors can deliver water, herbicides, and fertilizers precisely where they are needed, reducing waste and pollution.

2. **Labor Efficiency:** By eliminating the need for physical labor, automation of labor-intensive operations like planting, harvesting, and weeding improves farm productivity and sustainability (Bogue, 2016).
3. **Resource Optimization:** Sustainable resource management is promoted by advanced analytics derived from data collected by unmanned aerial vehicles (UAVs) and robotics, which aid farmers in optimizing the use of inputs including water, fertilizers, and pesticides (Mulla 2013).

18.10 Challenges

This section highlights the technological and regulatory hurdles that hinder the widespread adoption of climate-intelligent agricultural practices, including the use of robotics and UAVs.

18.10.1 Technological and Regulatory Hurdles

Technological Limitations: The adoption of robotics and UAVs in agriculture is hindered by technological challenges such as limited battery life, lack of robust communication networks in rural areas, and high initial costs of equipment and maintenance.

1. **Data Management and Integration:** Integrating data from multiple sources, including IoT devices, UAVs, and weather stations, poses challenges in terms of data storage, processing, and analysis, requiring advanced data management systems.
2. **Regulatory Frameworks:** The regulatory environment for UAVs and robotics in agriculture is still evolving, with issues related to safety, privacy, and airspace regulations needing to be addressed to ensure safe and legal operation.
3. **Skill and Knowledge Gaps:** For farmers to embrace modern technology, they need to learn new things. This might be especially tough for small-scale farmers who don't have much money to spend on education and training.

18.11 Future Trends and Potential Advancements

This section envisions the direction of climate-intelligent agriculture and emphasizes the need for continued research and development in this field.

18.11.1 Future Directions in Climate-Intelligent Agriculture

1. ***Enhanced Data Analytics:*** The massive amounts of data generated by sensors, UAVs, and the Internet of Things (IoT) will need the creation of advanced data analytics tools.
2. ***Automation and Robotics:*** Further progress in robotics will result in the development of agricultural robots that are increasingly autonomous and intelligent. These robots will possess the ability to carry out various tasks in agriculture, such as planting and harvesting, with minimal human involvement.

18.11.2 Call for Continued Research and Development

1. ***Innovation in Sustainable Practices:*** There is a need for innovative sustainable practices that can improve soil health, enhance water use efficiency, and reduce the environmental impact of agriculture (Lal, [2015](#)).
2. ***Policy and Regulatory Frameworks:*** Governments and policymakers need to develop supportive policy and regulatory frameworks that encourage the adoption of climate-intelligent agricultural technologies and practices.
3. ***Capacity Building and Training:*** Efforts should be made to enhance the capacity of farmers, researchers, and extension workers through training and education programs focused on climate-resilient agriculture.

Climate-intelligent agriculture has a bright future ahead of it, thanks to anticipated advances in science and technology that will promote resilient and sustainable farming methods. The achievement of the maximum potential of climate-intelligent agriculture in guaranteeing environmental sustainability and global food security will require sustained investment in research and development, in addition to policies that foster it and programs aimed at increasing capacity.

18.12 Conclusion

In the last portion of this chapter, we review the important aspects and lay forth a plan for academics, politicians, and farmers who want to use UAVs and robotics to make their crops more resistant to climate change.

18.12.1 Summary of the Chapter

This chapter examines how robots and unmanned aerial vehicles (UAVs) can work together to support climate-smart agriculture. It talks about how agriculture is being severely impacted by climate change and how robotics and UAVs might help. It also stresses how important it is to have access to high-resolution, real-time data so that decisions may be made with knowledge.

18.12.2 Roadmap for Researchers, Policymakers, and Practitioners

This chapter offers a guide for future research endeavors for researchers. These include incorporating artificial intelligence and machine learning into agricultural robotics, improving data analytics for handling extensive datasets, and creating crop varieties that are adaptable to climatic changes.

Policymakers are encouraged to develop supportive policy frameworks that promote the adoption of climate-intelligent agricultural technologies and practices. This includes incentivizing sustainable farming practices, investing in research and development, and providing training and education programs for farmers.

Practitioners are advised to explore the adoption of robotics and UAVs in their farming operations, considering factors such as technological feasibility, cost-effectiveness, and regulatory compliance. Collaboration among stakeholders is key to advancing climate-intelligent agriculture through knowledge sharing and technology transfer.

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Chapter 19

Methane Emission from Paddy Fields: Role in Climate Change and Possible Mitigation Strategies



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19.1 Introduction

By 2050, the Global population is predicted to expand to 9.7 billion people, leading to a substantial increase in the need for food and water. The production of food must increase by 70% to keep up with this growing demand (Poveda, 2021). However, excessive use of water, agrochemicals, and mineral fertilizers combined with intensive agricultural methods has resulted in land degradation, greenhouse gas emissions, pollution, and the exhaustion of natural resources. The production of rice worldwide will face one of the biggest obstacles as a rise in the global population is projected by 34% by 2050 (Tesfaye et al., 2021). Due to this rise, fertilizers—especially those containing nitrogen—will need to be applied more frequently, which will raise the release of greenhouse gases. Methane is a significant greenhouse gas

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responsible for environmental degradation. It has the capacity to produce 23 times more global warming than carbon dioxide. A significant reduction in methane emissions is required to maintain the temperature rise to 1.5 °C. Methane has a lesser atmospheric lifetime than carbon dioxide but an 80 times higher warming potential (UNEP-Convended Climate and Clean Air Coalition, 2024). Methane has raised global temperatures by 30% since the onset of Industrialization. Despite spending less time in the atmosphere than CO₂, it absorbs more energy (WMO, 2021). As of 2021, atmospheric methane concentrations had risen to an unprecedented 1896 parts per billion (ppb), 2.5 times higher than levels observed before the Industrial Revolution (IEA, 2024) (Fig. 19.1). According to the Sixth Assessment Report of the IPCC, methane concentrations in the atmosphere in 2021 (1896 ppb) exceeded those of nitrous oxide (335 ppb) and CO₂ (415 ppb). This indicates that significant reductions in CO₂, methane, and other greenhouse gas emissions are necessary to achieve net-zero emission targets (IPCC, 2023) (Fig. 19.1).

According to the most recent projections, the world emits about 580 Mt. of methane per year (IEA, 2024). Roughly 16% of GHG radiative emissions are methane-related (WMO, 2021). Methane's atmospheric lifetime is just approximately 12 years; therefore, cutting back on emissions can have a big impact on slowing down global warming (IEA, 2024). Methane emissions from human activity are increasing globally, especially from the agriculture, biomass industries, waste management, and Anthropogenic sources like rice farming, biomass, landfills, and fossil fuels burning are responsible for about 60% of these emissions; natural sources account for the remaining 40% (WMO, 2021). Methane and nitrous oxide are the two main greenhouse gases produced by humans and account for 14% of global emissions from agriculture alone (IPCC, 2014). Despite this, net emissions can be

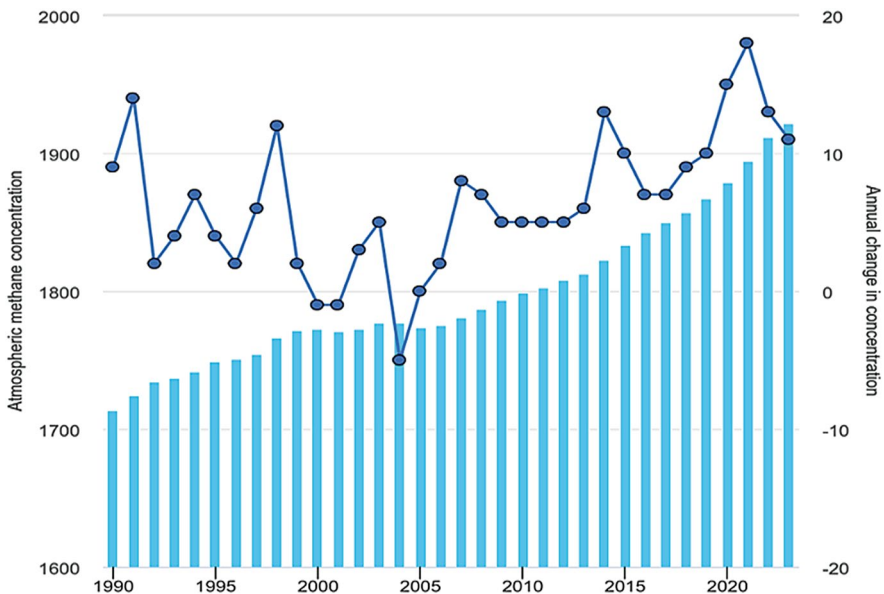


Fig. 19.1 Changes in atmospheric methane concentrations, 1990–2023 (data source: IEA, 2024)

decreased by carbon sequestration and the generation of bioenergy from agriculture. Major sources of terrestrial methane emissions are wetlands (~192 Mt), agriculture (~140 Mt), energy sectors (~127 Mt), waste (~72 Mt), and biomass burning (~10 Mt) (IEA, 2023) (Fig. 19.2). According to the global methane assessment, rice production contributes 8% of the global man-made methane emissions, or almost 40% of total emissions (UNEP-Convended Climate and Clean Air Coalition, 2024).

Since rice is the most consumed cereal worldwide and is a staple crop farmed on over 150 million hectares worldwide, it is imperative to emphasize the importance of rice paddies. Anthropogenic emissions of carbon dioxide, methane, and nitrous oxide are emitted during the cultivation of paddy rice and are a significant cause of climate change (IPCC, 2014). In terms of its contribution to CH₄ emissions, this agricultural practice comes in second only to enteric fermentation, which accounts for 22% of all agricultural CH₄ emissions worldwide (Smartt et al., 2016). Methane makes up roughly 30% of all anthropogenic emissions worldwide, while 9–11% share of agricultural GHG emissions come from rice (IPCC, 2014). Furthermore, the world's 11% of agricultural nitrous oxide emissions originate from rice (Zhang et al., 2021). India is a significant contributor to global methane emissions, ranking fourth in the world behind the US, China, and Russia with 658.09 Mt. CO₂ in 2019. In 2016, India accounted for 17.5% of releases of greenhouse gas from agriculture and 3% of the nation's overall emissions (71.32 Mt. CO₂), having the greatest area (43.19 million hectares) devoted to rice cultivation worldwide (Vetter et al., 2017; Fagodiya and Pathak, 2023). India contributes 26% of the world's rice production, which highlights its substantial involvement in methane emissions (USDA, 2023).

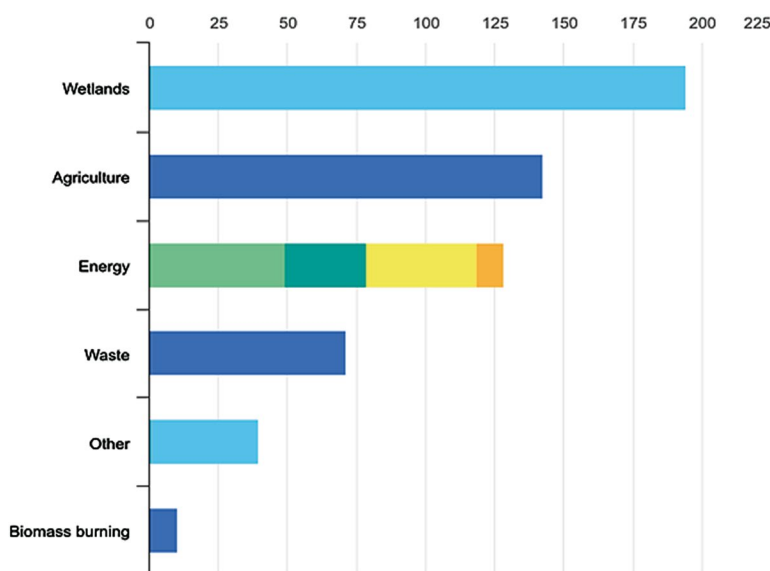


Fig. 19.2 Source of terrestrial methane emission (Mt) in 2023 (data source: IEA, 2023)

In view of the above, understanding the fundamental chemistry and mechanisms of methane generation and release is essential, especially in light of the significant release of methane from paddy. In light of this, the purpose of this review is to investigate the methane cycle in paddy fields and its relationship to climate change. It will cover the fundamentals of methane synthesis, oxidation, and transportation as well as the transfer processes from paddy fields to the atmosphere. It will also offer mitigation techniques to lower CH₄ emissions from paddy soils, supporting global warming mitigation efforts.

19.2 Emissions of Methane from Rice Fields

Methane emissions come from both biological and non-biological sources. Seas, Wetlands, landfills, ruminants, and paddy fields are examples of natural sources; on the other hand, burning biomass and fossil fuel-related activities including mining, production, and transportation are examples of non-biological sources. Both source types can have natural or man-made origins. Because they are the only crop that is regularly flooded, rice paddies are special because they provide an anoxic atmosphere that encourages the synthesis and release of methane (IPCC, 2014). According to Mboyerwa et al. (2022), compared to maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) systems, rice farming has a 2.7–5.7 times higher global warming potential due to methane emissions, which account for over 90% of the potential for global warming.

19.2.1 Global Methane Emission Scenario

Rice-based farming releases large quantities of methane, and the amount of water in the root zone has a big impact on gas production. Around the world, tropical, subtropical, and certain temperate boreal zones including Southeast Asia, Africa, and Central and Latin America are home to the majority of methane emissions from paddy fields (Aselmann & Crutzen, 1989) (Fig. 19.3). The main cause of emissions of methane from agriculture in Asia is rice fields. Asia produces the majority of the rice grown globally, with 90% of the fields in this region submerged in water (Wassmann et al., 2009). Anaerobic conditions produced by flooded soils are favorable for methanogens to synthesize methane.

The rising demand for rice in Southeast Asian nations with large populations, like China, India, Bangladesh, Thailand, and Cambodia, is increasing methane emissions. One kilogram of rice is thought to produce 100 g of methane that is released into the surroundings. Ninety percent of methane is released from paddy fields in Southeast Asia only, where annual contributions amount to about 10,000 kg km⁻¹ of methane (Yan et al., 2009). Methane emitted from rice in South America and Africa accounts for 4.7% and 3.5% of worldwide methane emissions, respectively.

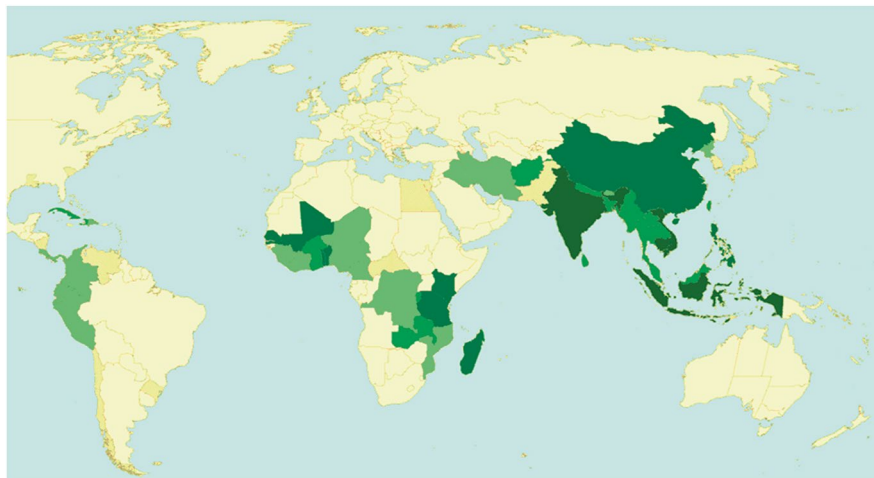


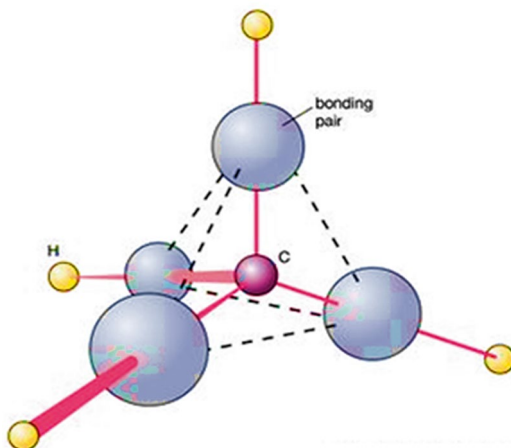
Fig. 19.3 World's high-intensity rice growing area, with high methane flux (data source: Aselmann & Crutzen, 1989)

According to a study, 80 million hectares of cultivated wetland paddy fields could potentially be sources of methane. Neue et al. (1990) predicted that over a typical 130-day growing season, methane emissions would average 200–500 mg/m² based on experimental data. This would translate to annual world emissions of 25–60 Tg. This is in contrast to Matthews and Fung's (1987) larger estimates of 40–160 Tg/year. After reviewing measurement data, Sass (1994) estimated that China was the largest emitter of rice, with 13–17 Tg from 32.2 million hectares, and proposed a lower emission range of 25–54 Tg/year from 147.5 million hectares rice area. Denier Van Der Gon and Neue (1996) projected a total release of 60 Tg/year using an IPCC default emission factor, with notable contributions from China (20 Tg) and India (25 Tg). Additional parameters that affect emissions include salinity, alkalinity, organic matter concentration, and drainage conditions, as noted by Denier van der Gon and Neue (1996). Methane release estimates decreased from approximately 80 to 40 Tg/year when seasonal emission observations were included, according to Van Bodegom (2000). Emissions of methane per hectare of rice crop in India varied from 36.56 to 47.22 kg in 2022 (Pazhanivelan et al., 2024).

19.2.2 Chemistry of Methane

Being the most basic organic compound and the final by-product of organic carbon breakdown in anoxic environments, methane (CH₃) is a special kind of molecule. It is a hydrocarbon that is a member of the paraffin series. Methane is an odorless, colorless gas that is both plentiful and created by a variety of human activities. It is less dense than air, with a specific density of 0.554 and a chemical formula of CH₄

Fig. 19.4 Chemical structure of methane molecule

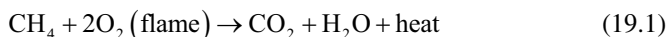


(Fig. 19.4). Methane ignites quickly in the air to produce carbon dioxide and water vapor with a pale, bright, and very intense flame, while being just slightly soluble in water (Uddin et al., 2003a, b). The melting and boiling points of methane are -182.5°C and -162°C , respectively. Methane-air mixtures that range from 5% to 14% methane by volume are explosive even though they are normally stable. Before delving into the specifics of methane's chemistry, one must have a basic understanding of its reactions.

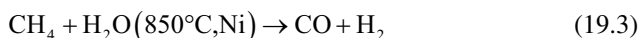
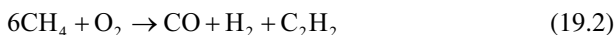
19.2.2.1 Combustion (Oxidation)

The process of burning methane, which commonly serves as a source of energy for heating, cooking, and power production, produces carbon dioxide (CO_2), water (H_2O), and heat. Methane also reacts with oxygen (O_2).

(a) Complete Oxidation Methane completely combusts with oxygen to produce carbon dioxide, water, and heat (Kossyi, 2001) (Eq. 19.1).

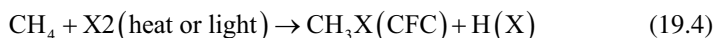


(b) Partial Oxidation Under high temperatures, methane partially oxidizes to form carbon monoxide, hydrogen, and acetylene. With steam and a nickel catalyst, methane converts to carbon monoxide and hydrogen (Kossyi, 2001) (Eq. 19.2 and 19.3).



19.2.2.2 Halogenation

Methane reacts with halogens (chlorine or bromine) to produce a halomethane (methyl halide) and hydrogen halide. This reaction, facilitated by heat or light, is more reactive with chlorine than bromine and does not occur with iodine. Chlorofluorocarbons (CFCs) are synthesized through a series of halogenation reactions starting with methane. Initially, chlorine atoms are introduced to form chloromethane, which can further react with fluorine to produce various CFC compounds (Han et al., 2010) (Eq. 19.4).



19.3 Methanogenesis: Biogeochemical Processes of Methane Production in Paddy Fields

Wetlands are crucial ecosystems that regulate hydrogeographic basins and preserve biodiversity. Many creatures use soil as their primary habitat, and the location and vegetation of the soil influence the biogeochemical cycles. Organic matter decomposes in wetland rice fields to produce gaseous by-products like methane and carbon dioxide. There are two primary pathways for CH_4 production in the soils of submerged condition (Neue and Scharpenseel, 1984), which include (Eq. 19.5 and 19.6):

Reduction of carbon dioxide with hydrogen (coming from organic substances):



Decarboxylation (transmethylation) of acetic acid:



The breakdown of organic materials under anaerobic conditions involves a diverse microbial community that culminates in methane production. This process progresses through several stages: initial hydrolysis by microorganisms breaking down complex polymers into simple sugars, fermentation of these sugars into organic acids by fermentative bacteria, conversion of fermentation products into acetate by homoacetogenic or syntrophic bacteria, and finally, methanogenesis, where methanogens produce CH_4 using various substrates including hydrogen, carbon dioxide, acetate, methylated compounds, or alcohols (Conrad, 2007).

Methanogenic bacteria are the primary contributors to methane emissions in paddy rice fields, thriving in anaerobic environments where they convert organic carbon into methane through methanogenesis. In the rice field ecosystem, methanogens and methanotrophs inhabit distinct niches such as shallow oxic surface layers of flooded fields, bulk soil, organic plant waste, and roots of rice plants (Conrad,

2007). The decomposition of organic sources like rice straw, root cells, and soil organic carbon fuels methane production, with approximately 80% of methane emissions originating from rice straw alone (Conrad, 2007). The abundance of methanogens can be assessed using molecular techniques like fluorescent microscopy and gene-specific primers.

Carbon sources for methanogenesis in rice paddies originate from root exudates, organic substances, and detritus of plants, as well as from soil organic matter. The majority of methane escapes into the atmosphere through rice's aerenchyma, with additional methods including ebullition and diffusion via surface water. Methanotrophs in the rhizosphere along with near-surface soil layers oxidize a portion of the methane produced under oxic situations (Butterbach-Bahl et al., 1997). Moreover, direct diffusion during drainage may release a sizable amount of methane that has been held in the soil. The equilibrium between the synthesis of carbon dioxide and methane is influenced by variables like temperature, soil pH, and organic material. In flooded rice, iron (III), manganese (IV), oxygen, nitrate, and sulfate are successively reduced to form methane, which serves as electron acceptors to oxidize organic substances into carbon dioxide. Root exudates in rice paddies play a crucial role as carbon sources for methane production, with a significant portion of photosynthesized carbon allocated to root exudation in the rhizosphere (Marschner, 1995).

The release of methane from rice exhibits a seasonal rhythm; increased emissions during the wet season and coincide with documented decreases in rice yield. However, methane emissions are decreased, and irrigated fields of rice frequently provide higher yields when the weather is dry. This has given rise to the theory that methane emissions and grain yields are inversely correlated. Research has validated this theory, observing reduced harvest indices in wet seasons when emissions of methane are higher compared to dry seasons when emissions from rice are low.

19.4 Methanogens and Methanotrophs- Key Driver of Methanogenesis

Studies have been conducted on the roles of soil microorganisms, such as methanogens and methanotrophs, in controlling atmospheric trace gases. Methanogens are specialized microbes that fall under the phylum Euryarchaeota and domain Archaea. They can produce methane in the presence of stringent anaerobic conditions and low redox potentials (150 mV). These organisms use a variety of substrates, including formate, ethanol, acetate, H_2 , and CO_2 , to obtain energy. As a metabolic by-product, they produce methane. About 80% of the methane produced during methanogenesis comes from acetate, which is the main carbon source. The remaining 10–30% comes from formate and H_2/CO_2 (Chen et al., 1993). With the *nif* gene,

methanogens from the three orders Methanomicrobiales, Methanomicrobiales, and Methanococcales may fix molecular nitrogen, although they normally rely on NH_4^+ for nitrogen. Methane release from organic matter and energy generation depends on important proteins such as coenzyme ferredoxin and methyl-coenzyme M reductase (Conrad, 2007). According to Bloom and Swisher (2010), methanogenic bacteria are a broad category of physiological kinds that include methylotrophic, obligatory chemolithotrophic, and quasi-chemolithotrophic microorganisms.

Additionally, research shows that methanogen populations usually increase in tandem with paddy growth, while methanotroph populations are generally not greatly impacted by irrigation and fertilization techniques (Minamikawa et al., 2006). Furthermore, studies have repeatedly shown that despite changes in field management techniques, methanogen populations, and community structures are generally stable (Table 19.1).

Methane-oxidizing bacteria in paddy soils can be categorized into methanotrophs and autotrophic ammonium-oxidizing bacteria. Methanotrophs, such as Methylocysti and Methylosinus, are aerobic microbes that exclusively use simple carbon compounds like CH_4 and methanol as their primary substrates. These bacteria are dependent on molecular oxygen (Bedard and Knowles, 1989). They are found in anaerobic soil layers and microsites where methane oxidation limits the upward passage of methane. These bacteria are found at the interfaces where oxygen and methane gradients meet. Methane monooxygenase (MMO) is an enzyme that helps oxidize methane by converting its reducing equivalents, CH_4 , O_2 , and water into methanol and water. According to Zhao et al. (2011), the release of methane is greatly regulated by the equilibrium between methane synthesis and oxidation, which lowers the amount of methane released into the surroundings when methanotrophic bacteria metabolize it when oxygen is available. These aerobic microbes can be found when oxygen is available, in the rhizosphere and the oxic top layer of flooded rice soil. Methanotrophs and methanogens are interdependent in the methane cycle. Water regimes have an impact on methane production by methanogens and the mitigation of its release into the atmosphere by methanotrophs.

Table 19.1 Methanogen populations and community structures

Location	Type of methanogen	Population (g^{-1} dry soil)	Reference
Senegal	Methanogens (general)	10^2 – 10^7	Garcia et al. (2000)
Italy	Cetotrophs	10^4	Mayer and Conrad (1990)
Italy	Hydrogenotrophs	10^6	Mayer and Conrad (1990)
Japan	Hydrogenotrophs	10^3 – 10^4	Asakawa and Hayano (1995)
Japan	Methylotrophs	10^4 – 10^5	Asakawa and Hayano (1995)
Japan	Acetotrophs	10^4 – 10^5	Asakawa and Hayano (1995)

19.5 Methane Emission Pathways from Rice Field

Methane emissions from rice occur through three primary mechanisms: ebullition, diffusion, and transportation facilitated by the rice plants themselves. The predominant route for methane release is through the rice plant's aerenchyma, constituting approximately 80–90% of total emissions. Ebullition, the bubbling of methane gas through waterlogged soil, contributes about 20–10% of emissions, while diffusion via the soil and water layer accounts for the remaining 1%. Studies have indicated that the release of methane from rice cultivation is regulated by a number of variables including rice cultivars, water management techniques, and soil conditions. To effectively reduce methane emissions while maintaining rice production, it is imperative to comprehend these pathways and their respective contributions.

19.5.1 Ebullition

Ebullition is a major mechanism in methane emissions, according to research, especially in rice fields and wetland habitats. One important process that raises atmospheric methane levels is the release of methane that has been stored in soil and sediments through gas bubbles (Fig. 19.5). Methane trapped in peat and sediments is released into the atmosphere as gas bubbles, which is a known and significant source of methane emissions. According to Wassmann and Martius (1997), this process enables methane to escape from the soil as bubbles, which makes it a significant source of emissions from sediments and accounts for 49–70% of the overall

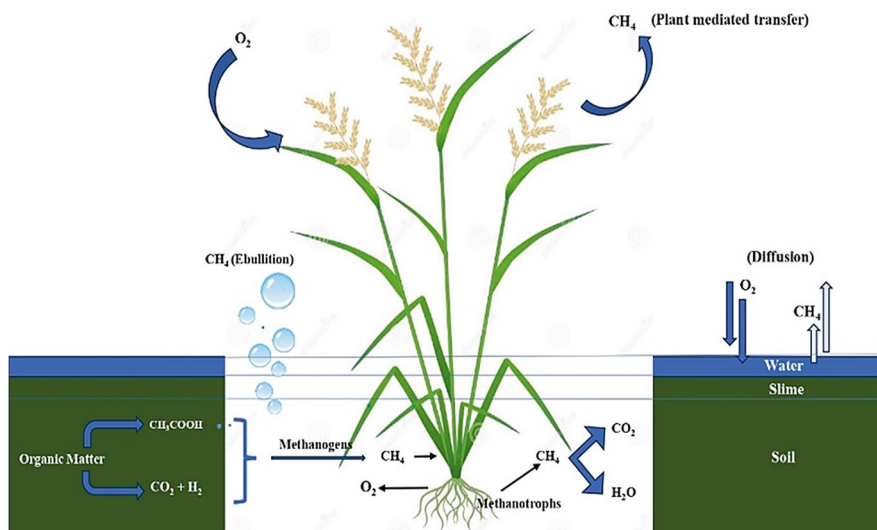


Fig. 19.5 Different pathways of methane emission

flux in natural wetlands. Methane ebullition in rice fields mostly happens early phase of rice growth and when farming is being done. During these operations, disturbances in the soil may release more methane that has been trapped there, which increases the ebullition emissions. Wind speed, flooding, humidity, solar radiation, water table, floodwater level, and air pressure are some of the factors that affect ebullition. According to studies, the release of methane from fields devoid of paddy is half that of fields that are planted, with ebullition responsible for almost all of the emissions in unplanted areas. Methane ebullition occurs during early flooding phases when rice plants are small, according to research by Takai and Wada (1990) in Japan. As plants mature, vascular transport becomes more dominant. Additionally, ebullition is crucial in situations when there is bare soil or poorly formed plant aerenchyma. It mostly happens at the surface layer of soil and is impacted by temperature, methane content, soil porosity, and the development of aerenchyma.

19.5.2 Diffusion

The diffusion of methane from water and soil is significant for the emissions of methane from paddy fields. A number of variables, such as the quantity of methane in surface water, wind speed, and the amount of methane that enters the water, affect how much methane is emitted into the surroundings from flooded paddy fields. Gas diffusion is substantially slower in water rather than in air, which limits gas exchange in soils saturated with water. The overall contribution of methane emissions in the rice growing season is generally just 1–2% due to the dispersion of CH₄ (Butterbach-Bahl et al., 1997). The majority of CH₄ generated is oxidized which contributes very little to the overall CH₄ flux from rice fields. Moreover, plant-mediated transport—which is similar to a chimney effect—is the main emission mechanism of methane from rice (Wassmann et al., 2000).

19.5.3 Plant-Mediated Transfer

Due to their capacity to transport methane primarily through plant-mediated pathways can make up to 90% of the total flux of methane transit. The dynamics of methane releases from rice depend substantially on rice plants, resembling chimneys (Wassmann et al., 2000). Rice and other aqueous wetland plants create a specialized tissue called aerenchyma to help them deal with flooding. The main researcher's particular photograph demonstrates how rice plants growing in wet settings exhibit more pronounced aerenchyma development than plants seeded directly. Methane is released when it dissolves in water around the roots, permeates into the root epidermis cells' cell-wall water, followed by moves through the root cortex's cell-wall water due to variations in concentration. Lysigenous intercellular spaces and aerenchyma carry the gas from the root cortex to shoot; the majority of

emissions come from stomata in the leaf blade and micropores of the lower leaf sheath. Research shows that as rice plants get older, oxidized CH_4 levels rise and plant-mediated CH_4 emission contributes more (Schutz et al., 1989). According to Wang et al. (1997), during the early growth phases leaf blades accounted for around 50% of CH_4 emissions. However, as plants grew older, alternative channels, like cracks at internode junctions, became more important. Unless leaves and nodes are submerged, panicle emission of CH_4 is low, and the quantity of nodal culms closely correlates with emission rates (Wang et al., 1997). Three key roles are played by rice plants in methane dynamics: they provide methanogenic substrates, act as CH_4 conduits through large aerenchyma, and diffuse oxygen to enhance methanotroph growth in the rhizosphere, potentially creating methane-oxidizing microenvironments. To sum up, plant-mediated transport, specifically diffusion at the root–shoot junction, is primarily responsible for the facilitation of release of the methane.

19.6 Factors Affecting Methane Emission

19.6.1 Temperature

Temperature is a crucial deciding factor that has a positive correlation with CH_4 generation. An increase in soil temperature results in enhanced methane emission from the paddy field. The ideal temperature for methanogenesis in permanently submerged soil was 40 °C and raised to 45 °C when intermittent irrigation was applied, which was also associated with a considerable drop in the activity of methane-producing archaea (Hattori et al., 2001).

19.6.2 Soil Physicochemical Properties

Methanogenesis in reducing soil conditions is highly sensitive to pH having an optimal pH range of 6.7–7.1. Generally, CH_4 production begins at approximately –150 mV and is accelerated at less than –200 mV. The oxygen status in the soil profile is a key limiting factor that governs soil Eh and so regulates methane generation and oxidation (Bender and Conrad, 1993). As the availability of O_2 in the soil increases the oxidation of methane by the methanotrops also enhances, resulting in a decrease in methane emission.

19.6.3 Soil Texture

CH_4 emissions and the clay content of soil are negatively correlated. Clay minerals can inhibit the decomposition of organic matter and higher clay content can promote CH_4 sequestration in soil (Wang et al., 1993) and subsequently reduce net CH_4

emissions. Calcareous soils produce CH_4 quickly after flooding (Neue and Roger, 1994), possibly because CaCO_3 acts as a buffer of pH at microsites where methanogenesis occurs. Soils with coarse texture and strong percolation rates frequently have positive redox potential. In such soils during rice cultivation, CH_4 production is projected to be significantly reduced.

19.6.4 Organic Matter Content

CH_4 production and emission from the flooded paddy fields is strongly dependent on the availability of carbon, which usually comes from manures, leftover plant residues, and root exudates of the rice plants. The application of rice straw and farmyard manure as organic manure in the soil leads to a boost in methane emissions (Pandey et al., 2014). In aerobic settings, organic matter emits carbon dioxide, while in anaerobic situations, it produces methane. However, treated organic materials like biochar or charcoal, break down more slowly than fresh non-treated organic material, resulting in lower methane emissions.

19.6.5 Rice Cultivar

Different rice types emit varied amounts of CH_4 from the submerged rice fields. These variances may be attributed to root architecture and the structure and distribution of aerenchyma cells (Aulakh et al., 2002). High root biomass has been associated with higher CH_4 production. Methane emissions are typically higher in high-yielding rice varieties than in low-yielding varieties (Malyan et al., 2016). The formation of root litter and root exudates in rice plants, which contain carbohydrates and amino acids, can facilitate CH_4 synthesis by providing substrates for methanogenesis (Jia et al., 2001). Root exudates are a significant contributor to methanogenesis during the rice ripening stage as they contain acetate which acts as a substrate for CH_4 formation.

19.6.6 Paddy Growing Stages

During the initial stages of paddy crop development, methane emissions are typically lower. This could be because there is not much methanogenesis at that time. High levels of methane emissions were detected during the reproductive and grain filling and hardening stages. This was most likely driven by the increasing availability of fatty acids and carbs during the period (Bharti et al., 2001). The highest CH_4 emission occurs during the ripening phase of rice, which is caused by easily degradable organic matter released from the roots.

19.6.7 *Agricultural Practices*

19.6.7.1 Fertilization

Organic fertilizers, such as manure, compost, and crop residues, are effective in improving the availability of essential nutrients and increasing microbial diversity and activity in rice fields. The utilization of organic fertilizers in flooded rice fields leads to an increase in the carbon pool, which translates into increased CH₄ emission and a significant shift toward dominant methanogens (Zhou et al., 2016). CH₄ production in rice fields can be boosted by the application of N. Application of N as ammonium form to flooded rice soils can reduce CH₄ oxidation (Wassmann et al., 1993) and the CH₄ emission into the atmosphere can be increased. Reductions in CH₄ emissions associated with NO₃-N use were attributed to competitive inhibition of nitrate reduction in favor of methanogenesis. Application of sulfate fertilizer can reduce CH₄ formation in anaerobic conditions as both sulfate-reducing bacteria competes with methanogens for the substrate.

19.6.7.2 Water Management

Flooding in the fields reduces the amount of oxygen and other gases in the soil, including sulfates. This situation enhances methanogenesis activities, releasing more CH₄ into the environment. Intermittent drainage has an advantage in improving soil oxygenation status, which leads to increased root activity and increased soil's carrying capacity, which ultimately reduces the excess water to bring oxygen into the soil environment, leading to reduced methane production. Intermittent draining systems reduced methane emissions by 61% compared to complete submergence, with no significant variations in rice dry matter or grain yield (Wihardjaka, 2015). Nitrogen absorption and soil oxidation conditions are improved through mid-season drainage. Mid-season drying for 20 days at 19 DAT, i.e., starting of mid-tillering stage, caused low CH₄ emission where the rate of methane flux from 19 to 30 DAT hiked by 13.6 mg m⁻² day⁻¹ in flooded rice plots (Wassman et al., 2000).

19.6.7.3 Cultural Operations

Soil disturbance during harrowing, transplanting, weeding, fertilizer, and pesticide application and harvesting can cause soil-entrapped CH₄ to be released into the sky. During the weeding of a rice field in the Philippines, CH₄ emissions increased significantly (Neue et al., 1994). Soil drying after harvesting the rice crop may result in significant CH₄ emissions, especially in fine-textured soils that crack when dried.

19.6.7.4 Crop Residues

Straw additions to rice fields result in a several folds rise in CH_4 emissions. The addition of 5 tonnes of rice straw into the soil could boost CH_4 emission ten times compared to inorganic fertilizers (Neue et al., 1996). The most substantial increment in CH_4 emissions after straw amendments was observed in partially burnt residues. Rice stubbles or straws were incorporated into the soil by tillage before flooding to allow them for initial aerobic decomposition, which reduced CH_4 emissions. Similarly, composting rice straw before inclusion into the crop may lessen the straw-induced CH_4 emissions by 20% (Corton et al., 2000). Field burning of agricultural leftovers also releases CH_4 , N_2O , and other minor greenhouse gases. Organic matter found in rice straw plays a crucial role in maintaining the carbon cycle of rice fields but leads to heightened CH_4 emissions.

19.7 Measurement and Monitoring of Methane Emissions

Greenhouse gases are significantly influencing the ongoing climate change globally. Although determining the precise consequences of human activity is difficult, it is well known that excessive greenhouse gas emissions from human activity are a contributing factor to global warming. More than 20% of the increase in global radiative forcing from the pre-industrial period may be attributed to greenhouse gases like CH_4 . At the moment, a variety of effective methods are employed to quantify and estimate methane emissions, and new methods are constantly being developed. However, none of these methods are without drawbacks, necessitating careful evaluation before their application. Understanding the strengths and weaknesses of experimental methods is crucial in planning experiments and interpreting both personal findings and published research from other scientists (Storm et al., 2012).

19.7.1 Field-Based Methods

The closed chamber systems are the most frequently employed techniques in measuring the methane emission in fields of rice (Aulakh et al., 2001). In order to measure methane fluxes from rice fields, air samples must be continually collected in chambers. The concentration of CH_4 ideally shows a linear change during enclosure. Manual sampling is cost-effective but requires frequent collection to reliably assess flux rates due to diurnal and seasonal variations. Flux rates measured between 6 and 8 h generally provide consistent indicators of nocturnal emissions, whereas observations made between 13 and 14 h typically capture the peak diurnal emissions.

(a) Chamber techniques The chamber technique demonstrates high accuracy and precision in measuring daily CH_4 production from animals housed within, yet its capability is restricted in terms of handling larger numbers of animals simultaneously. Air cooling, internal air mixing, and meticulous sealing are features of conventional energy metabolism chambers that lessen the chance of air leakage into the adjacent area (Derno et al., 2009).

(b) Eddy covariance Rinne et al. (2007) demonstrated that the eddy covariance measuring device could measure even the tiniest methane fluxes during the winter and could effectively capture the emission surge during the snow-melting season. The chamber technique has been used extensively in research on methane emissions from wetlands.

(c) Remote sensing Advanced remote sensing technologies like thermal infrared imaging and/or light detection and ranging (LiDAR) can directly measure area emissions, surpassing current estimation methods. These techniques are especially well-suited for measuring fugitive emissions because they can evaluate areas inaccessible to in situ methods due to location or safety constraints, provide extensive spatial coverage over hundreds of meters, and typically do not rely on assumptions about the precise locations of emission sources. Thoroughly validating emission measuring systems is essential to instill trust in users and regulators on the dependability of these technologies and to promote their use. When creating emission measurement instruments, developers frequently use strict quality assurance procedures, regardless of whether they use in situ or distant sensing techniques. Among these is the use of internal calibration gas cells to guarantee measurement uniformity and accuracy (Robinson et al., 2011). Spectral reflectance of plants provides an indirect means for optical sensors to evaluate the characteristics of beneath marsh soil.

19.7.2 Laboratory Methods

The laboratory method for measuring methane emissions typically involves using specialized equipment to analyze air samples collected from chambers or directly from the atmosphere. This method allows for controlled conditions and precise measurements of methane concentration over specified periods, providing valuable data for understanding emission rates and environmental impacts (Shaw et al., 2021).

(a) Incubation experiments Scaling and correlation factors for methane oxidation parameters were obtained using laboratory incubation studies on homogenized soil samples in order to forecast the genuine rates of methane oxidation in the field. A warming field experiment with anaerobic incubation of soil samples from the Barentsburg glacial melt water river showed no difference in microbial composition or CH_4 concentration across temperatures, but warming accelerated microbial respiration, increasing CH_4 flux over at least 2 weeks. In comparison to the GR site, the

GR-0 site produced more CO, indicating the necessity for longer-term research to comprehend how global warming affects CH₄ emissions in the Arctic (Li et al., 2023).

(b) Gas chromatography Ramin et al. (2011) found that varying the concentrate levels (40:60 vs. 60:40, barley silage) did not significantly affect CH₄ emissions when nutshell extract, a methane inhibitor, was used in vitro. The relationship between MFA concentrations and methane emissions has been examined in a number of studies, and milk fatty acid (MFA) profiles are advised as a sign to estimate CH₄ emissions in dairy cows. The prediction accuracy for CH₄ emissions (in L/d) was low when using models derived from FTIR spectra and CH₄ measurements taken by the automated milking station sniffer technique (Shetty et al., 2017)

19.7.3 Modeling Emissions

The closest distance to the source, the instruments at hand, and the current weather all influence the measuring technique selected. Although various methods have been used, including Gaussian plume modeling, Bacharach Hi-Flow Sampler, static and dynamic chambers, and backward Lagrangian stochastic models, their relative accuracy and precision are yet unknown (Riddick et al., 2022).

Utilizing simulation models to calculate emissions in different situations: The integrated agricultural system model (IFSM) has new modules for predicting extra greenhouse gas emissions and simulations of CH₄ emissions from all agricultural sources. A basic hydrologic model was created to simulate the location of the water table in wetlands. Data from multiple wetland locations were used to evaluate this model, and its vulnerability to variations in precipitation was examined. The global methane-hydrology model is a tool used to study the geographical and temporal variability in methane emissions from natural wetlands. The Moe and Tyrrell model was used to simulate the production of methane in cattle (Moe and Tyrrell, 1979).

19.8 GHG Mitigation Strategy from Rice Field

Methane released from rice fields is a significant issue in agricultural sciences due to its considerable contribution to global warming. Rice-based cropping systems result in substantial production and exchange of methane to the atmosphere which is affected by the availability of water in the rhizosphere. Methane is formed due to the degradation of organic substances anaerobically in submerged rice fields through synthesis, oxidation, and transport. With the continuously growing population and their dietary shifts, the global need for rice continues to escalate, so it is necessary to explore sustainable agricultural strategies for mitigating the release of methane (Hussain et al., 2020).

The emission of methane can be minimized using various agronomic practices including modification of irrigation and drainage practices, management of organic substances and fertilizers, selection of suitable cultivars, and managing microbial populations. Comprehensive studies on the heterogeneity and viability of methane mitigation techniques along with the influencing factors that regulate methane emission are still lacking (Ma et al., 2024). This chapter considers the scientific methods and technological advancements intended to minimize rice field methane emissions along with preserving or enhancing crop yields and soil quality. By understanding and adopting these approaches, we can support global endeavors to prevent climate change and promote sustainable agriculture practices.

19.8.1 Water Management Practices

Methane emissions have been found to be greatly affected by water. Changes in watering conditions can alter the redox potential of soil; hence the water regime should regulate methane emissions (Xiaohong et al., 2011). Anaerobic bacteria produce methane in anoxic conditions by transmethyating acetic acid or reducing carbon compounds. Conventional farming involving frequent flooding causes significant release of methane into the atmosphere, so proper maintenance of the field condition through water management is an essential component in growing rice and an effective methane mitigation strategy. Irrigation approaches including alternate drying and wetting, mid-season drainage, controlled irrigation, and intermittent irrigation significantly lower the methane release from the field (Malyan et al., 2016). Table summarizes several water management techniques that could reduce the release of methane from rice fields.

19.8.1.1 Mid-Season Drainage

This method involves a certain interval between irrigations over a crop during the growth season and fields might be temporarily drained to lower methane emissions. Mid-season drainage suppresses methane emissions and increases the productivity and quality of rice by regulating nitrogen absorption and maintaining oxidative soil conditions. Consequently, limiting the amount of water used could be an effective strategy as methane emissions will eventually drop with a reduction in water consumption.

19.8.1.2 Alternate Wetting and Drying (AWD)

This method includes periodical draining of rice fields instead of constant flooding. Unlike mid-season drainage, the duration between wet and dry instances is too short to allow the conversion of aerobic to anaerobic conditions in the soil. By

periodically permitting the soil to dry out, AWD inhibits the anaerobic conditions that promote methane generation which ultimately lowers methane emissions. Dry conditions make soil aerobic which allows methanotrophs to oxidize methane (Minamikawa et al., 2006).

19.8.1.3 Intermittent Irrigation

It involves periodic irrigation and appropriate drainage, improves soil oxidative conditions, and carrying capacity, and eventually lowers water requirements that lead to anoxic conditions. It raises the amount of oxygen that permeates the soil, increasing the aerobic zone and reducing the production of methane (Yagi et al., 1997).

19.8.1.4 Controlled Irrigation

Controlled irrigation minimizes the net greenhouse gas emission from transplanted flooded rice. The soil remains dry (60–80%) throughout the season by preventing flooding once rice seedlings regreen (Peng et al., 2011). Likewise, the water conservation strategy was implemented in the System of Rice Intensification (SRI) (Table 19.2).

Table 19.2 Potential water management techniques for minimizing the release of methane from rice field

Water management practices	Description	Mitigation potential (%)	Reference
Mid-season drainage	Method of draining all flood water from a field for around 7 days during the last stages of tillering.	43	Corton et al. (2000)
		36	Zheng et al. (2000)
		37	Tyagi et al. (2010)
Alternate wetting and drying	Method of controlled and intermittent irrigation allowing the field to occasionally dry out after irrigation rather than continuously flooding it.	73	Katayanagi et al. (2012)
Intermittent irrigation	Method of irrigating the field intermittently, allowing the soil to dry out between the water applications.	38	Yagi et al. (1996)
		26	Minamikawa and Sakai (2005)
Controlled irrigation	Managing water supply to maintain optimum soil moisture without continuous flooding.	27	Hou et al. (2012)
		67	Yang et al. (2012)

19.8.2 Soil Amendments

The quality of soil significantly influences the discharge of methane by influencing the generation and release of this gas. Soil pH, redox potential, oxygen concentration, soil temperature, and soil organic substances greatly influenced methane production. Introducing soil amendments into the soil is an effective approach to lowering methane emissions, also improving the physical, chemical, and biological conditions. Organic amendments including biochar, crop residues, and various other organic matter can improve soil structure, increase the proportion of organic substances in soil, and encourage microbial diversity (Lehmann et al., 2011). These modifications may result in a change in the microbial community, favoring methanotrophic bacteria over methanogenic archaea, which create methane (Conrad, 2007). In addition to reducing methane emissions, applying these amendments to rice also increases crop production, improves soil fertility, and supports sustainable farming practices.

19.8.2.1 Organic Matter

Methane emissions are frequently raised by the inclusion of organic matter including farmyard manure, plant residues, and weed residues. Methanogens synthesize methane from organic substances in the soil (Kimura et al, 2010). These organic substances are degraded into acetates or alcohols by methanogens, methane-producing bacteria. Eliminating straw application to rice fields could be a useful strategy as it reduces methane emissions as compared to incorporating straw in the field. Residue incorporation about 60 days before sowing of rice is more advantageous for both yield and methane emission as compared to applying just before transplanting. Compared to when straw is incorporated, surface retention of straw may reduce methane emission (Zschornack et al., 2011).

19.8.2.2 Biochar Application

Biochar is a substance obtained from the pyrolysis of organic materials that effectively enhances crop yield along with reducing methane emissions. Applying biochar into soil can enhance soil quality, facilitate soil aeration, and lower methane emissions. It also lowers methane emissions by modifying the functions and dynamics of the microbes, lowering the amount of carbon sources available for methanogenesis, and improving soil carbon sequestration. Applying biochar significantly decreases methane emissions by 20–80% depending on the amount and kind of biochar used (Zhang et al., 2012). Table 19.3 summarizes the reduction rates of CH₄ after applying biochar with other chemical fertilizers in the paddy fields.

Table 19.3 Reduction in emission of methane by using biochar in paddy fields

Techniques	Methane emission reduction	Reference
Application of biochar	38–41%	Nan et al. (2020)
Application of biochar with urea	33.8%	Kim et al. (2017)
Biochar comprising slow-release fertilizer	33.4%	Dong et al. (2021)
Application of biochar	20–51%	Wang et al. (2018)
Application of biochar	47.30–86.43%	Dong et al. (2013)

19.8.3 Crop Management

Most of the methane released from rice fields into the environment (60–90%) via the rice aerenchyma instead of moving across water-air surfaces by molecular diffusion (Wassmann et al. 2000) and emitted by the leaf blade stomata (Das and Baruah, 2008). Different rice cultivars have differing capacities for releasing methane because of variations in root exudation, plant physiology, and microbial interactions in the root zone. Thus, selecting and growing rice with low methane transport capacity with higher yield is a suitable option for reducing methane emissions (Das and Baruah, 2008). This section describes some efficient crop management practices including the selection of cultivars, cultivating low methane-emitting varieties and their mode of transplanting greatly influence the release of methane from the rice.

19.8.3.1 Selection of Cultivar

Methane emissions varied significantly among rice varieties under the same circumstances. The weight of the plant is inversely correlated with methane emission that is heavier varieties fix more carbon and produce less methane. Compared to conventional rice, hybrid rice emits methane at a reduced rate along with producing a higher yield as high-yielding varieties retain more nutrients in the plant that is the source of methanogenic bacteria (Jia et al., 2006). Thus, the cultivation of hybrid rice reduced methane emissions while simultaneously raising yields. Early-maturing varieties can be cultivated to successfully lower CH₄ emissions from paddy soils. Additionally, research has shown that early-maturing varieties have a considerable impact on soil methanogen and methanotroph abundance, which in turn affects CH₄.

19.8.3.2 Low Methane-Emitting Varieties

Methane synthesis, oxidation, and release are greatly impacted by rice plants (Butterbach-Bahl et al, 1997). In rice fields, root exudates include carbon molecules that provide methanotrophic bacteria with sustenance results in the formation of

methane. Rice varieties with higher yields release less methane than conventional varieties. Mitigation efforts can be enhanced by breeding and adopting rice varieties with reduced methane emissions because of variations in aerenchyma structure and root exudation. The Heijing 5 variety exhibits a lower release of methane due to a decline in microbial activity in the root zone (Hu et al., 2023).

19.8.3.3 Method of Transplanting

Compared to conventional transplanting, techniques like SRI and direct-seeded rice can produce less methane from the field by eliminating the need for continuous flooding during the seedling stage. Direct-seeded rice ensures oxygen in the soil for the majority of the rice season due to its shorter flooding period around 1 month as it eliminates the raising nurseries, puddling, and transplanting, reducing methane emission. System for Rice Intensification Compared to traditional transplanted rice can increase rice yield while using roughly 22–35% less water thus reducing methane emission. This process can lower the methane emission by 29% (Rajkishore et al., 2013).

19.8.4 Fertilizer Management

Fertilizer management has an important impact on minimizing methane production and release by controlling rice plant growth, methanogenic microbial community activity, and the volume and root exudate components of rice plants (Aulakh et al., 2001). Variations in fertilization techniques, including type and rate of application, invariably result in variations in soil qualities that influence the microbial communities that have grown over time. Slow-release fertilizers can indirectly affect soil redox potential and decrease the anaerobic zones which encourage the growth of methane-producing bacteria. Table 19.4 summarizes the reduction in methane release rates in paddy fields through the application of different fertilizers.

19.8.4.1 Optimized Fertilizer Use

Optimum use of fertilizer shows significant results in lowering methane emissions. Ammonium-based nitrogen fertilizers can decrease the emission of methane by up to 50% (Dong et al., 2011). Under aerobic conditions, it has been shown that applying sulfate fertilizers enhances methane oxidation. The use of potassium can also lower methane emissions by 49% (Jagadeesh Babu et al., 2006).

19.8.4.2 Use of Slow-Release Fertilizers and Nitrification Inhibitors

The application of slow-release nitrogen fertilizers is an ideal approach to lower the release of methane from rice by regulating the release of nutrients. This steady release helps the rice plants have a more consistent source of nitrogen and minimizes the amount of excess nitrogen available in the soil, which could encourage methanogenic activity. Methane emissions can be efficiently managed by using nitrification inhibitors like neem oil, neem cake, and dicyandiamide along with slow-release nitrogen fertilizers (Li et al., 2009). The use of dicyandiamide, along with proper water management approaches exhibits a certain level of methane reduction. Paddy soil treated with slow-release nitrogen fertilizer shows the lowest methane emission along with maximum yield compared to other conventional nitrogen fertilizers (Zhang et al., 2016).

19.8.4.3 Use of Biofertilizer

Biofertilizers, which consist of living microorganisms that promote plant growth by providing essential nutrients, can substantially reduce the release of methane. Biofertilizers including mycorrhiza, cyanobacteria, diazotrophs, and Azollae significantly improve soil characteristics, enhance yield, and minimize methane emissions. Biofertilizers can alter the microbial community of soil by boosting the population of advantageous microorganisms such as methanotrophs (methane-oxidizing bacteria) and minimizing methanogens (methane-producing archaea) (Yagi et al., (1996). Applying biofertilizers like arbuscular mycorrhiza effectively minimizes methane emission by lowering root biomass, the release of exudates, or inhibiting the activity of methanogenic bacteria. Azollae can lower emissions as they raise dissolved oxygen, which promotes methanotroph oxidation. However, the efficacy of biofertilizers in reducing methane emissions still needs to be evaluated.

Table 19.4 Reports on the emission of methane in the application of different fertilizers

Application	Methane emission (kg ha ⁻¹)	References
No nitrogen fertilization	24.5	Ghosh et al. (2003)
Urea @ 120 kg N ha ⁻¹	37.3	
Ammonium sulfate @ 120 kg N ha ⁻¹	33.0	
No nitrogen fertilization	95.3	Cai et al. (1997)
Ammonium sulfate @ 100 kg N ha ⁻¹	55.0	
Urea @ 100 kg N ha ⁻¹	88.4	

19.8.4.4 Fermentation of Manure

Incorporating fermented manures induces lower methane emission by causing quick depletion of soil organic matter pool. Incorporating fermented residues can lower methane emissions by around 60% and 52% in comparison to fresh substances and a mixture of urea and organic substances, respectively (Wassmann et al., 2000). Fermentation of manure decreases the amount of readily degradable organic matter that is the main source of methane production in rice. Complex organic components in manure are broken down into simpler substances during anaerobic digestion, resulting in a more stable material that contains fewer precursors of methane.

19.8.4.5 Application of Silicon

Silicate fertilizers, a steel manufacturing by-product with a considerable concentration of iron oxide, used as a potential oxidizing agent in rice cultivation, additionally supply enough silica required for healthy growth of rice. Silicon enhances photosynthetic efficiency and growth, which results in higher biomass production. This increased biomass can increase the intake of water and nutrients, and decrease the amount of organic substances that are accessible for anaerobic breakdown, hence reducing methane emissions. Silicate fertilizers increase root oxygen exudation, improve methanotrophic bacteria activity, and decrease methane emissions by encouraging root growth. In addition, the presence of active iron oxide silicate fertilizers boosts the activity of iron-reducing bacteria which reduces methanogenesis activity and ultimately reduces methane emission (Liang et al., 2007).

19.8.5 Microbial Management

The amount of methane released from paddy fields, which is dependent on both methane generation and oxidation is influenced by the activity and variety of methanogens and methanotrophs in soil (Conrad, 2007). Methanotrophs are suitable species for limiting CH₄ emission as the fluctuations in methanotrophic activity are primarily responsible for variations in CH₄ emission from paddy fields. Consequently, increasing methanotrophic population size or activity can minimize the formation of methane. Promoting the growth of microbes that consume methane or inhibit its production can be an effective strategy for mitigating methane emissions. Naturally, methane is originated by methanogenic microbes in the oxygen-depleting soil layer beneath the aerobic layer. Methane moves through the aerobic layer and possesses a greater amount of oxygen. Methanotrophic bacteria located in that layer absorb 90% of the methane, acting as a barrier to methane emission (Hornibrook et al., 2009).

19.9 Policy Implications for Mitigating CH₄

Because agriculture releases non-CO₂ gases including N₂O and CH₄ from the production of crops and livestock, it accounts for 20% of global greenhouse gas emissions over a 20-year period. This has a big effect on climate change (OECD, 2021). After livestock, the cultivation of rice is the agricultural activity that emits the most methane. According to estimates, methane discharges from rice fields unaided might contribute between 31 and 112 Tg/year to global CH₄ emissions, or almost 19% of all emissions (Win et al., 2020). Since the 2015 Paris Agreement, which committed 196 countries to a legally binding agreement to keep global warming well below 2 °C, and ideally below 1.5 °C, plummeting GHG emissions in the agriculture sector has gained importance (UNFCCC, 2015). Reducing emissions from the agricultural sector—mostly CH₄ and N₂O—can make a substantial difference in plummeting the possessions of climate change (Lynch and Garnett, 2021).

19.9.1 *International Policies*

19.9.1.1 Global Methane Pledge

The US and the EU launched the worldwide methane pledge, a project aimed at cutting worldwide CH₄ discharges by a minimum of 30% from 2020 levels by 2030. At the UN Climate Change Conference (COP26), which took place in Glasgow in November 2021, this pledge was made. Because methane has a major impact on climate change, the promise highlights the significance of reducing methane emissions across many sectors, including energy, agriculture, and waste management. Joining the promise, more than 100 nations—which collectively account for over half of the world's anthropogenic methane emissions—have demonstrated a common commitment to lowering methane emissions and mitigating the consequences of climate change (European Commission, 2021).

19.9.1.2 Paris Agreement

A worldwide framework to address climate change was established in 2015 to keep temperature far beneath 2 °C, with efforts concentrated on maintaining it at 1.5 °C over pre-industrial levels. This agreement is known as the Paris Agreement. The agreement encourages nations to incorporate methane reduction plans in their nationally specified contributions (NDCs), even though it does not expressly target methane emissions. This is because methane is a strong GHG that has a big effect on global warming. Therefore, a lot of the signatory nations to the Paris Agreement have acknowledged the significance of methane reduction in reaching their overall climate goals (Rogelj et al., 2018).

19.9.1.3 FAO's Global Methane Assessment

The global methane assessment was fashioned by the Food and Agriculture Organization (FAO) to assist member nations in developing and putting into practice policies to lower methane emissions from agriculture. The status of methane as a powerful GHG is emphasized in this evaluation, which also provides thorough advice on mitigation best practices and technology. The FAO hopes that by offering these guidelines, nations would be able to better match their agricultural practices with global climate targets, which will help to reduce methane emissions globally (Gerber et al., 2013).

19.9.2 National Policies

19.9.2.1 United States Policies on Methane Emissions Reduction

(a) Methane Emissions Reduction Act The United States' Methane Emissions Reduction Act seeks to encourage technological advancement and offers cash rewards to farmers who implement methane emission-reducing techniques. In order to promote a more sustainable agriculture industry, this legislation encourages the research and application of ground-breaking technology and techniques to decrease CH₄ emissions from agricultural sources (Smith et al., 2021).

(b) USDA Programs: Environmental Quality Incentives Program (EQIP) The Environmental Quality Incentives Program (EQIP), managed by the United States Department of Agriculture (USDA), delivers financial and technical support to farmers and landowners so they can adopt conservation techniques, such as lowering methane emissions. The installation of anaerobic digesters is one noteworthy method that EQIP supports. By capturing methane and turning it into biogas, can be utilized as a renewable energy source, these digesters assist in managing manure in a way that lowers overall methane emissions (USDA, 2023).

19.9.2.2 European Union Policies on Methane Emissions Reduction

(a) Common Agricultural Policy (CAP) The EU's Common Agricultural Policy (CAP) offers a number of incentives designed to cut greenhouse gas emissions, including methane. Through financial incentives and technical assistance, CAP promotes the adoption of sustainable agricultural techniques by farmers. These methods involve reducing methane emissions from cattle by using cutting-edge technologies, optimizing animal feeds, and managing manure better. The sustainability emphasis of CAP aids in bringing agricultural practices into line with the EU's more expansive climate goals (European Commission, 2023).

(b) National Emission Ceilings (NEC) Directive The National Emission Ceilings (NEC) Directive imposes legally enforceable obligations on EU member states to reduce emissions of important pollutants, such as methane. In order to reach their emission reduction targets, member states are required by the NEC Directive to cre-

ate national plans and report their progress to the European Commission. By imposing stringent restrictions on the total emissions of each member state, this directive seeks to lower overall emissions and enhance air quality while guaranteeing a coordinated strategy to reduce methane emissions throughout the EU (European Environment Agency, 2021).

19.9.2.3 Australia: Emissions Reduction Fund (ERF)

(a) Emissions Reduction Fund (ERF) An Australian administration program called the Emissions Reduction Fund (ERF) provides financial incentives to land executives and farmers to implement strategies that lower greenhouse gas emissions, including methane. The ERF offers financial incentives for confirmed emissions reductions made using authorized techniques. These techniques include employing anaerobic digesters, better-managing manure, and enhancing livestock feed to decrease enteric fermentation. Farmers can profit financially from lowering methane emissions by participating in the ERF and generating Australian Carbon Credit Units (ACCUs), which they can sell to the government or private buyers.

19.9.3 Socioeconomic Challenges

The adoption of methane reduction practices in rice farming is impeded by several significant barriers, including high upfront costs and uncertain returns on investment, which deter farmers from adopting new technologies (Arunrat et al., 2018) (Fig. 19.6). Adoption rates are further constrained by limited technical and

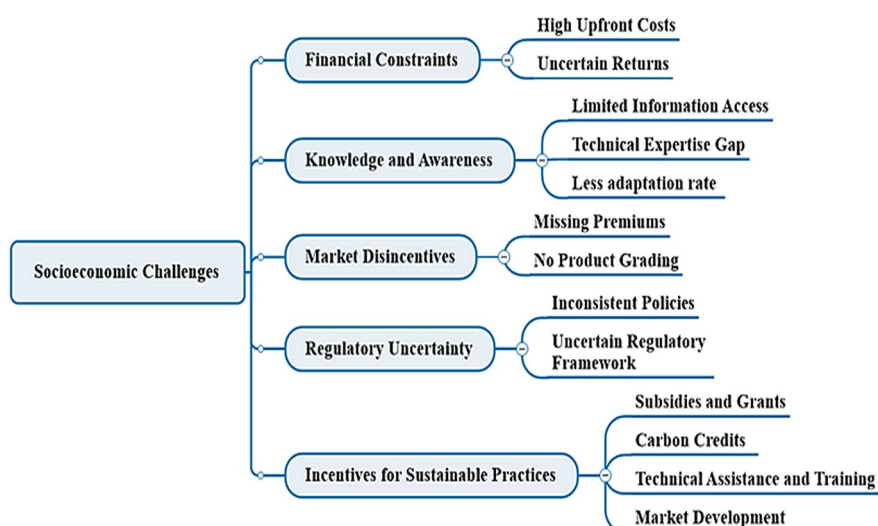


Fig. 19.6 Constraints and uncertainties in adopting methane reduction practices in rice farming

informational access, particularly in developing nations (Sánchez et al., 2016). Farmers' financial incentive to grow rice sustainably is diminished in the absence of market incentives such as premiums. Additionally, inconsistent policies and regulatory frameworks create uncertainty, making farmers hesitant to invest in sustainable practices (Farrukh et al., 2024). Overcoming these barriers requires financial assistance programs, carbon credit opportunities, technical training, and the development of market demand for sustainably produced agricultural products.

19.10 Conclusion

Methane discharges from rice fields are a significant contributor to global methane levels, impacting climate change. Understanding the global methane emission scenario underscores the substantial role that paddy fields play in this environmental issue. The biogeochemical processes of methanogenesis in paddy fields, driven by methanogens and methanotrophs, are key to understanding methane production. Various pathways of methane emission from these fields have been identified, with numerous factors influencing the emission rates, including soil properties, water management, and agricultural practices. Addressing these emissions is crucial for climate change mitigation, and implementing effective GHG extenuation strategies in rice cultivation can significantly reduce methane output, contributing to global efforts to combat climate change.

Acknowledgments The corresponding author appreciates the collaboration and support of the co-authors in preparing and finalizing the manuscript.

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Chapter 20

Enhanced Efficiency Fertiliser (EEF) Intervention for Climate Change Resilience



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20.1 Introduction

Agriculture is at high risk due to the impacts of climate change and higher temperatures, more irregular precipitation and the occurrence of extreme weather events disturbing food production and food safety (Akanmu et al., 2024; Nji et al., 2022). Nevertheless, the agricultural industry not only serves as a source of greenhouse gas (GHG) emissions but also plays a substantial role in contributing to environmental deterioration, primarily due to the poor utilisation of fertilisers. Hence, optimising the utilisation of fertilisers is crucial in agriculture to enhance its ability to withstand climate change and simultaneously minimise the adverse effects on the environment.

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20.1.1 Importance of Efficient Fertiliser Management for Climate Resilience in Agriculture

The climate change issue is currently one of the most troubling issues for agricultural output and food safety around the globe (Ahmed et al., 2019). Crops are susceptible to serious damage from rising temperatures, shifting precipitation patterns, and more frequent and severe weather events like heat waves, floods, and droughts (Challinor et al., 2014). In addition, farmers must contend with issues such as soil erosion, water scarcity, pest infestations, and disease outbreaks, all of which are made worse by climate change.

One way to improve farming systems and lessen the problems created by unfavourable climatic conditions in agriculture is through efficient management of fertilisers. Crops that utilise nutrients efficiently are better able to endure environmental stressors and sustain productivity during times of climate change. In a similar vein, using effective fertilisation techniques will strengthen the soil's resilience and encourage water conservation, which will help agricultural systems adapt to the effects of climate change (Atapattu et al., 2017; Dissanayaka et al., 2023a, b, c).

20.1.2 Environmental Impacts of Inefficient Nutrient Use

The utilisation of fertilisers is undoubtedly essential to the replenishment of soil depletion and to enhance crop yields; however, when the nutrients are not properly managed, the environmental impact may be very grave. Intense and mismanaged fertiliser application could mean nutrients being leached, runoff, and volatilised, which would result in both water pollution and ecosystem degradation and greenhouse gas emissions (Ashitha et al., 2021).

Reactive nitrogen losses from agricultural systems are one of the leading issues. Nitrous oxide (N₂O), which has a high greenhouse effect, is released from soils by the activities of microorganisms involved in fertiliser nitrogen application. The term nitrate leaching from agricultural fields penetrates the ground water bodies and surface water risking human health and aquatic ecosystem (Khan et al., 2018). Moreover, ammonia volatilisation fuelled by fertilisers is also an important contributor to air pollution and the formation of particulate matter, thus, endangering the health of humans and ecosystems (Behera et al., 2013).

20.1.3 Overview of Enhanced Efficiency Fertilisers (EEFs)

Enhanced efficiency fertilisers (EEFs) is the concept of improved fertiliser formulations and application methods avoiding the issue of inefficient usage of nutrients which also allows the crops to be more resilient against the negative effects of

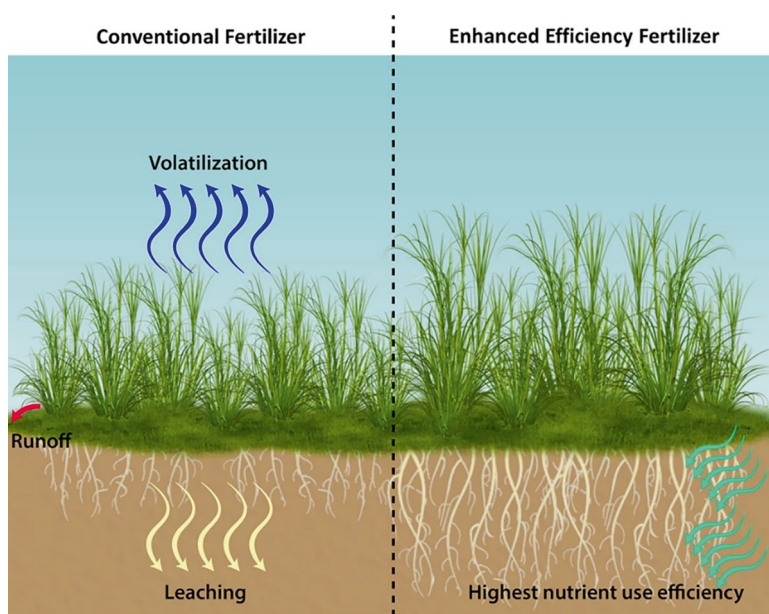


Fig. 20.1 Conventional fertiliser vs. enhanced efficiency fertiliser

climate change and poorly capable of nitrogen losses (Lam et al., 2022). These science-based EEFs allow about 40% to 45% of nitrogen inputs to be allocated precisely to the required locations and seasons, avoiding losing nutrients to the environment (Fig. 20.1).

20.2 Nitrification and Urease Inhibitors

Nitrogen is a vital nutrient for plants to thrive and develop its proper utilisation is an important factor contributing to the improvement of yields as well as reduction of environmental harm. Nitrification and urease inhibitors serve as key functions in controlled-release fertilisers allowing nitrification and urea hydrolysis processes to undergo controlled processes. In the following section, the processes will be analysed, types of inhibitors used in practice, their effect on nitrogen use efficiency and performance and environmental risks and limitations.

Nitrification and urea hydrolysis are processes that are particularly relevant to the nitrogen cycle, especially in agricultural systems, affecting both the efficiency and environmental impact of fertiliser use.

20.2.1 Processes of Nitrification and Urea Hydrolysis

Ammonia (NH_3) or ammonium (NH_4^+) are first oxidised to nitrite (NO_2^-) by the ammonia-oxidising bacteria in the two-step biological process known as nitrification. Nitrite-oxidising bacteria then proceed to oxidise nitrite to nitrate (NO_3^-). The resulting nitrate is very mobile in the soil and can easily leach through the water runoff or be denitrified back to nitrogen gas thus significantly reducing the nitrogen use efficiency (Ayiti & Babalola, 2022). Urea hydrolysis is the process where urea fertilisers are broken down by urease enzymes, which are naturally present in the soil as well as the plant surfaces. This enzymatic reaction produces ammonium carbonate, which breaks down into ammonia (NH_3) and carbon dioxide (CO_2). Under the conditions of high pH such as alkaline soils, the ammonia produced particularly volatilises with nitrogen losses being quite significant under specific environmental conditions. This release not only represents a loss of a useful nutrient but also contributes to atmospheric pollution causing unwanted deposition of nitrogen in certain places which may subsequently harm the environment (Klimczyk et al., 2021).

20.2.2 Types of Nitrification Inhibitors

Nitrification inhibitors (Table 20.1) are designed for agricultural use to reduce the rate of conversion of ammonium to nitrite which ultimately lowers the risk of nitrogen losses that occurs due to leaching and denitrification (Fig. 20.1). Such inhibitors govern nitrogen use efficiency, which ensures the prolonged release of fertilisers.

Table 20.1 Different nitrification inhibitors and their mode of action

Nitrification inhibitor	Mode of action	Reference
Nitrapyrin	Selectively inhibits the activity of ammonia-oxidising bacteria, slowing down the first step of nitrification.	Hayden et al., (2021)
Dicyandiamide (DCD)	Inhibits both ammonia-oxidising and nitrite-oxidising bacteria, delaying the entire nitrification process.	Ning et al. (2018)
3,4-Dimethylpyrazole Phosphate (DMPP)	Inhibits the first stage of nitrification by preventing ammonia monooxygenase enzyme activity.	(Shi et al., 2016)
2-Amino-4-chloro-6-methylpyrimidine (AM)	Inhibits the activity of ammonia monooxygenase enzyme, inhibiting the first step of nitrification.	Gupta et al., (2023)
3,4-Dimethylpyrazole Succinic Acid (DMPSA)	Inhibits the activity of ammonia monooxygenase enzyme, inhibiting the first step of nitrification.	Corrochano-Monsalve et al., (2021)

Table 20.2 Different urease inhibitors and their mode of action

Urease inhibitor	Mode of action	Reference
N-(n-butyl) thiophosphoric triamide (NBPT)	Forms a temporary complex with the urease enzyme, effectively inhibiting its activity and reducing ammonia volatilisation from urea fertilisers.	Klimczyk et al. (2021)
Phenyl phosphorodiamidate (PPDA)	Binds to the urease enzyme and inhibits its activity, slowing down the hydrolysis of urea.	Saggar et al. (2013)
Hydroquinone	Inhibits the urease enzyme by reacting with its active site, reducing ammonia volatilisation from urea fertilisers.	Modolo et al. (2018)
2-Nitrophenylphosphoric Triamide (2-NPT)	Forms a temporary complex with the urease enzyme, inhibiting its activity and reducing ammonia volatilisation.	Klimczyk et al. (2021)

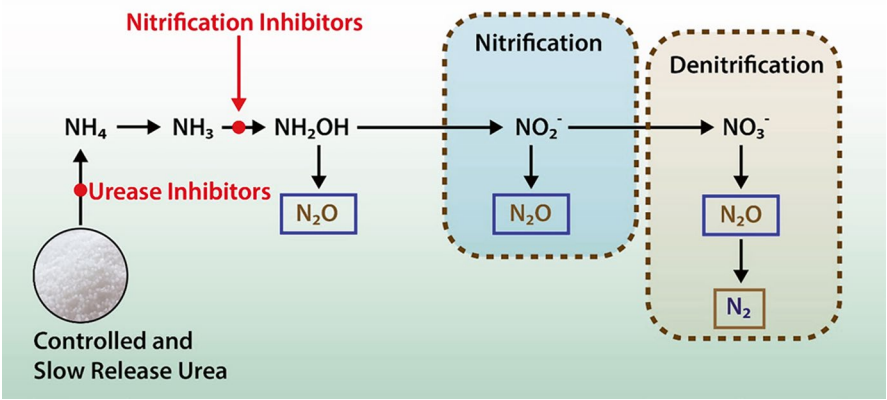


Fig. 20.2 Mechanism of nitrification and urease inhibitors

20.2.3 Types of Urease Inhibitors

The urease inhibitor (Table 20.2) refers to the compounds that restrict urease enzyme activity, thereby slowing urea hydrolysis down and at the same time, minimising ammonia losses (Fig. 20.2). Soil and plant surfaces naturally contain an enzyme known as urease which catalyses the hydrolysis of urea which is a popular fertiliser used around much of the vegetation.

20.2.4 Effects on Nitrogen Use Efficiency and Yield

The use of nitrification and urease inhibitors in controlled-release fertilisers is a key innovation to be used along with other methods to ensure proper and effective utilisation of nitrogen for enhanced crop production. By addition of denitrification

inhibitors can significantly reduce nitrogen emissions through leaching, denitrification, and ammonia volatilisation. The process of nitrogen mineralisation is thus inhibited therefore more of nitrogen is preserved in the soil in forms that plants can readily absorb and benefit from. This allows for more nitrogen, a plant's essential source of food, to be retained in the soil and therefore becomes more available for the plants to use (Lawrencina et al., 2021). Azeem et al. (2014) indicate that when the availability of nitrogen is released in a controlled way from fertilisers and the action of nitrification and urease inhibitors are combined, a stable and reproducible nitrogen supply is provided. This coordination also ensures that nitrogen is available with greater ease in stages of growth that would better match the exact needs of fertilising crops as they grow. This timely provisioning can result in the betterment of both yields and quality of the crops because plants can draw the nutrients precisely when needed, which optimises their growth and pulls productivity up to the maximum.

Environmental benefits and limitations CRFs including nitrification and urease inhibitors are an excellent alternative to conventional fertilisers which also have constraints. Shaviv (2000) underscores that CRFs can minimise nitrate leaching into groundwater virtually by slowing down nitrification, thus tackling nitrate pollution which is responsible for the deterioration of quality and health of aquatic ecosystems. Luna Juncal et al. (2023) pinpoint the fact that applying urease inhibitors in CRFs considerably diminishes ammonia volatilisation, which is a major nitrogen loss way in agriculture, therefore curbing air pollution and its harmful effects such as the generation of particulate matter and smog contribution. Lawrencina et al. (2021) highlight that since CRFs have a good nitrogen use efficiency they cut down on the quantity of extra fertiliser application hence bringing down the direct environmental impact and also the greenhouse gas emissions associated with the fertilisers' production and transport. Furthermore, Azeem et al. (2014) highlight that there are several challenges associated with the massive spread of CRFs such as higher upfront investments, restricted distribution in certain regions, and their compatibility with specific crop systems. They often deter agricultural activities, particularly in marginal areas or regions, where costs prevail over the benefits. Nevertheless, CRFs can provide nutrient management services that could lead to improvements in environmental conditions, but their wider application depends on solving economic, logistical, and technical problems.

20.2.5 Biofertilisers with Nitrogen-Fixing Microbes

Nitrogen is a major macronutrient for a plant; therefore, its deficiency may limit crop productivity considerably. Incorporating nitrogen-fixing microbes-based biofertilisers represents a green and eco-friendly substitute for synthetic nitrogen fertilisers (Atapattu & Nuwarapaksha, 2025). Even more, these bacteria have the ability to extract atmospheric nitrogen and transform it into forms that plants can directly absorb, improving soil fertility and promoting plant development (Atapattu et al., 2020; Olanrewaju et al., 2024).

Mechanisms of biological nitrogen fixation Numerous microorganisms, including bacteria and archaea, participate in the process of biological nitrogen fixation. They are endowed with several enzymes that make nitrogenase enzyme work, which converts atmospheric dinitrogen (N_2) into ammonia (NH_3) (Boyd & Peters, 2013). The ammonia is taken by the microorganisms and assimilated in organic compounds or getting released for plants to uptake. The lengthy and energy-intensive process of nitrogen fixation necessitates an anaerobic or low-oxygen environment because the nitrogenase enzyme is very oxygen-sensitive. Some autotrophic biotrophic bacteria of the genus *Rhizobia* form symbiotic associations with leguminous plants, residing in specialised root nodules and receiving carbohydrates from the host plant in exchange for fixed nitrogen (Olanrewaju et al., 2022).

Types of Nitrogen-Fixing Microbes

Nitrogen-fixing microbes can be classified into several categories based on their ecological niches and associations with plants (Table 20.3).

Inoculation Methods and Application Techniques The application of biofertilisers containing nitrogen-fixing microbes can be achieved through various inoculation methods.

- **Seed inoculation:** Seeds are treated by mixing up the selected microbes with a suspension or by soaking them and before planting this mixture is used to control contact between the bacteria and the growing root system (Ali et al., 2019).
- **Soil inoculation:** Unlike chemicals that must be mixed with water and sprayed, the biofertiliser goes to the soil either by broadcasting or through targeted placement near the root zone (O’Callaghan et al., 2022).
- **Foliar application:** In some instances, microorganisms that fix nitrogen can be foliar sprayed so that they colonise the phyllosphere (leaf surfaces) (Preininger et al., 2018).

Table 20.3 Types of nitrogen-fixing microbes

Type	Ecological niche and association	Examples	Reference
Symbiotic nitrogen fixers	These microbes form intimate associations with plant roots, such as the rhizobia-legume symbiosis	<i>Rhizobium</i> <i>Bradyrhizobium</i> <i>Sinorhizobium</i> species	Kumar et al. (2020)
Free-living nitrogen fixers	These bacteria can fix nitrogen independently without forming symbiotic associations with plants	<i>Azotobacter</i> <i>Azospirillum</i> <i>Gluconacetobacter</i> species	Rashid et al. (2015)
Associative nitrogen fixers	These microbes colonise the rhizosphere (the region surrounding plant roots) and can fix nitrogen while benefiting from root exudates	<i>Azospirillum</i> <i>Herbaspirillum</i> <i>Gluconacetobacter</i> species	Van Dommelen and Vanderleyden (2007)
Endophytic nitrogen fixers	These bacteria reside within plant tissues, such as stems and leaves, and can contribute to nitrogen fixation	<i>Gluconacetobacter</i> <i>diazotrophicus</i> <i>Azoarcus</i> species	Gupta et al. (2012)

- **Seedling dip:** Seedlings are conditioned by dipping in a microbial suspension before planting which facilitates early root colonisation (Ali et al., 2019).

Proper inoculation techniques including the use of relevant carriers and adherence to recommended application amounts are keys for achieving the establishment and long-term survival of the infused microbes.

Effects on Crop Yield and Soil Fertility The use of biofertilisers harbouring microbes with nitrogen-fixing ability in crop production increases crop yield and soil fertility (Fadiji et al., 2022; Maitra et al., 2023a, b) by several means (Fig. 20.3). The microbes can fix nitrogen and balance the nitrogen level in the soil promoting plant growth and increasing yield (Li et al., 2017). On the other hand, some microbes inhabiting the rhizosphere have the potential to do more than just fix nitrogen. They can also solubilise phosphates and other nutrients, increasing their availability to plants (Richardson & Simpson, 2011). These microbes not only produce plant growth-promoting chemicals like phytohormones but also stimulate root development as well as overall plant growth (Ahemad & Kibret, 2014). Besides, the micro-organisms' activities contribute to the formation of stable soil aggregates which in return improve soil structure and water-holding capacity (Alori et al., 2017). The application of biofertilisers also reduces the usage of synthetic nitrogen fertilisers lowering groundwater contamination and greenhouse gas emissions (Diacono et al., 2019). The combination of these benefits results in sustainable and environmentally friendly agricultural practices.

Integration with Other Nutrient Management Strategies Combining the application of biofertilisers with other nutrient management has a significant impact on

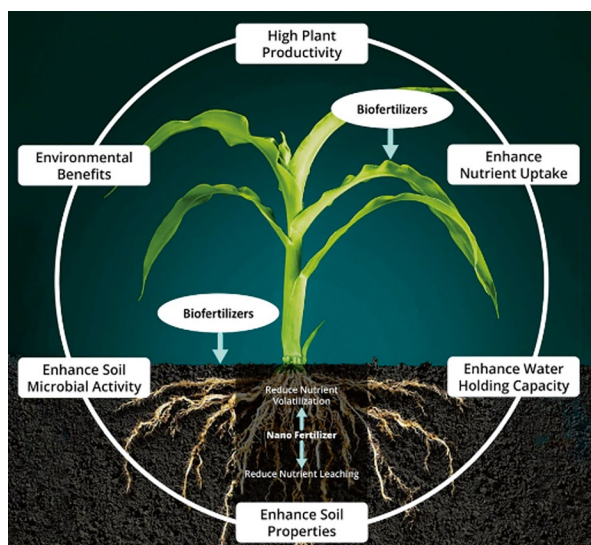


Fig. 20.3 Effects of biofertilisers

their efficacy and leads to sustainable agriculture. Organic amendments like compost (Dissanayaka et al., 2023a, b, c; Udumann et al., 2023a, b), manure, or biochar could be mixed with biofertilisers to provide other nutrients and improve soil conditions creating favourable conditions for nitrogen-fixing microbes (Dissanayake et al., 2023; Maitra et al., 2023a, b; Shamila et al., 2024). Crop rotation with nitrogen-fixing legume rotation is beneficial for the resupply of soil nitrogen (Nuwarapaksha et al., 2022, 2023a, b; Udumann et al., 2024). In addition, biofertilisers can be used together with chemical fertilisers reducing chemical inputs and providing the optimised crop yield. The adoption of conservation agriculture like minimal soil disturbance, maintaining ground cover with crop residues and cover cropping can encourage nitrogen-fixing microorganisms (Dissanayaka et al., 2022; Udumann et al., 2023a, b). Integrating these strategies helps farmers create a more sustainable, environment-friendly agriculture improving soil fertility and crop yields without excess use of synthetic inputs (Dissanayaka et al., 2023a, b, c, 2024; Atapattu & Udumann, 2024).

20.3 Science-Led Enhanced Efficiency Fertilisers for Precision Agriculture

The global need for food production keeps increasing and is determined by population growth as well as the change in diets. However, at the same time, the world is witnessing serious consequences of conventional agriculture methods, which involve the application of huge fertilisers, which have spurred the interest of the globe towards sustainable agriculture practices (Nuwarapaksha et al., 2023a, b). By the use of precision farming, which is a way of grooming farm practice by considering unique conditions, there has been an implication of a promising solution. EEFs, the growth of which is of pivotal importance in the management of nutrients and ensuring minimal consequences to the environment, are the ones to achieve these goals.

20.3.1 Tailoring Nutrient Doses to Crop Needs across Locations and Seasons

Conventional fertilisers are generally applied to fields at the same rate, which means they ignore the fact that these soil conditions, crops, and the Environment change over time and space. For instance, EEFs are fabricated in a way that they release nutrients in a constant manner which is specific to the various growth stages of the crop and also in different soil and climatic conditions (Dimkpa et al., 2020). Such a targeted nutrient delivery allows crops to receive the correct amount of nutrients at the precise time and place maximising the nitrogen use efficiency and the loss

reduction. Through the deployment of a range of EEF technologies, farmers will calibrate the supply of nutrients precisely to the individual needs of each crop at multiple spatial and temporal scales, to achieve maximum growth and yield without any detrimental effects on the environment.

20.3.2 Avoiding Over-Application of Fertilisers

Traditional fertiliser application methodologies frequently cause over-application which leads to excess nutrients embedding in the soil or being lost to the surroundings via leaching, runoff, or gas emissions. EEFs are developed to address this problem of nutrient regulation and preventing losses (Dimkpa et al., 2020).

Slow-release fertiliser manages the steady release of nutrients reducing nutrient loss spent on nutrients not being absorbed by crops and releasing them over a longer period of time. This, rather, makes nutrients absorbency higher by crops that ingest the available nutrients. Fertilisers with stabilised forms of nutrients are not subjected to nitrification and urease activities and as a result, nutrients like nitrogen do not leach with irrigation as well as evaporating when soils are dry.

EEFs along with technology of precision agriculture are anticipated to help mitigate over-application of fertiliser and ensure optimum utilisation (Snyder, 2017). This approach where the area gets subdivided into the smaller management zones depending on the soil differences, the nutrients requirement, the potential yields, and the transmission of the desirable quantities of fertilisers appears as the right choice.

20.3.3 Lowering Greenhouse Gas Emissions

Conventional fertilisers are widely referred to as the main sources of carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions into the atmosphere, as they are mostly produced, transported, used, and removed in agricultural activities (Shcherbak et al., 2014).

High nitrogen use efficiency, low nitrogen losses, and a less wastage emission from fertilisers can be achieved through the utilisation of EEFs. Nitrification inhibition highers the amount of N_2O emission thanks to the delay of ammonium to nitrates conversion (Ruser & Schulz, 2015). Urease inhibitors will lower ammonia volatilisation thus directly decrease N_2O gas emission which will further enhance the retention of nitrogen in the soil (Ren et al., 2023). Developing the precision agriculture system that is making use of the EEF led to the reduction of the fertiliser application rates, hence less emissions due to the manufacturing process, logistics, and field work (chemicals) (Atapattu et al., 2024).

20.3.4 Increasing Yields per Unit Input

Conventional fertiliser technologies commonly produce low-nutrient use efficiency and many nutrients that are applied are lost to the environment or remain unavailable to crops. EEFs along with precision agriculture techniques help crops to increase yield per unit of fertiliser input by enhancing nutrient accessibility and uptake (Karthik & Maheswari, 2020).

Through the synchronisation of nutrient release with crop demand, EECs make sure that nutrients are available when the plants request them the most and reduce losses as well as increase uptake. Through this delivery of targeted nutrients, not only yield is enhanced but also fertiliser efficiency is improved, and more yields are produced per unit of fertiliser applied.

Also, the integrated operation of EEF with other precision agriculture practices like soil moisture monitoring and variable rate irrigation ensures an optimal cropping condition and nutrient utilisation, resulting in higher yields at lower costs (Snyder, 2017).

Along with the rise of demand for sustainable and productive farming methods, the science-led EEFs will become more beneficial in making precision agriculture a reality. This is achieved through varying the nutrient rates, curtailing over-application, reducing greenhouse gas emissions, and increasing yields per unit input of nutrients which offer an alternative to more productive and ecological agricultural systems.

20.4 Economic Assessment of Enhanced Efficiency Fertilisers Adoption

The use of EEFs can be immensely beneficial to farmers through economic gains in varying crop systems and global regions. Initially, the EEFs may be more expensive than the traditional fertilisers in generating but their efficiency in facilitating nutrient efficiency, improving yields and reducing the environmental effects is what makes them economically viable.

In addition to agricultural top advantage, crops give more produce when absence of fertilisers. The EEFs are developed to be able to only release the level of nutrient that coincide with the period of plant growth—including a controlled nutrient escape—maximising crop nutrient uptake and utilisation (Dimkpa et al., 2020).

In this case, there will be economic gains on account of reduced fertiliser consumption thereby the environment preservation supported also and farming practices sustainable become obvious. The EEFs filling can prevent nutrients leaching and others outflows and releases. It is more convenient for famers to execute those environmental rules and prohibits them from fees imposed on them (Dimkpa et al., 2020).

In addition to, productive carbon dioxide emissions will yield revenue via carbon cap and trade system, and other developed programmes to promote an environmentally friendly farming that will in turn drive the sustainability of agriculture endeavours (Haïtes et al., 2018). In the background of this policy, we see the economy becomes ecologically friendly and the carbon emissions are controlled through the application of carbon tax.

20.5 Policy Priorities and Recommendations

The accelerated enrolment of EEFs allows for the widespread utilisation and this leads to sustainability of agriculture, environmental conservation, and improved farm economics. Yet, their true holistic potential is expressed with a should policy environment. Major areas of action include use of mobile apps and decision support tools for optimising nutrient application using EEFs (Lajoie-O'Malley et al., 2020), incentivising the use of precision agriculture equipment by offering subsidies and public private partnership arrangement to farmers (Paustian & Theuvsen, 2017), which eventually would lead to upgrade in the soil testing infrastructure Integration of efficient fertilisation strategies into national policies, public–private cooperation, awareness campaigns, and the alignment with agricultural and environmental sustainability activities (Dalgaard et al., 2014) are the key components of overall agricultural productivity.

Using digital tools for sophisticated fertilisation management requires specialised application machinery, accurate soil information, and trained extension officers (Nuwarapaksha, 2024a, b, c). Policy measures like financial support, capacity building, and infrastructure development can be employed as a key strategy to ensure that farmers adopt the so called for environmentally friendly farming practices (Atapattu et al., 2024). Furthermore, the policy making should both address the nutrient management at farms and on the sectoral basis.

An all-inclusive policy framework that deals with technology access, knowledge distribution and multi-sector collaboration will lead release of environmental, economic and production potentials of EEFs. Substantial funds and durable involvement of governments, research institutions and industries are necessary in implementing the space-based sustainable fertilisation method in order to use agriculture a tool for climate change resilience.

20.6 Conclusion

Science-based EEFs integrated with precision agriculture practices represents a platform to tackle the problem of raising food production while at the same time maintaining check on environmental degradation. EEFs are a new category of fertiliser and management techniques aimed at efficient nutrient use, mitigate losses, and

ensure farming sustainability through adapting fertiliser delivery to crop needs across sites and growth stages, the EEF ensures that crops receive the nutrients they require at the right amounts and places, to enhance yield while minimising the environmental consequences.

EEFs consist among other technologies of controlled-release coatings, nitrification inhibitors, urease inhibitors, and biofertilisers which are nitrogen-fixing microbes. Field trials have independently proven their ability to boost output, enhance efficiency, cut costs, and promote environmental protection. However, the successful adoption of EEFs is highly contingent on implementing proper policy.

Critical policy objectives are to scale up digitalised extension services for precision agriculture, motivate the implementation of smart application techniques, revamp infrastructure on soil testing and agricultural extension, and popularise efficient fertilisation across all sectors. Coordination, among governments, research institutions, and private sector players, remains critical for the resolution of challenges of technology dissemination, infrastructure development, and incentive systems.

As the world's demand for sustainable and efficient agricultural practices continues to increase, science-driven and precision agriculture EEFs supply a pathway towards productive and environment-oriented crop production systems, which is important for global food security without exploiting natural resources for future generations.

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