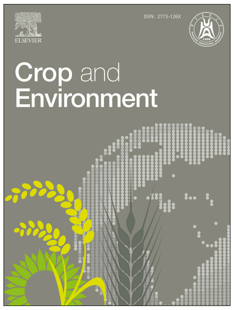

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# Effects of climate change on plant pathogens and host-pathogen interactions

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## Abstract

Crop production stands as a pivotal pillar of global food security, but its sustainability faces complex challenges from plant diseases, which pose a substantial threat to agricultural productivity. Climate change significantly alters the dynamics of plant pathogens, primarily through changes in temperature, humidity, and precipitation patterns, which can enhance the virulence and spread of various plant diseases. Indeed, the increased frequency of extreme weather events, which is a direct consequence of climate change, creates favorable conditions for outbreaks of plant diseases. As global temperatures rise, the geographic range of many plant pathogens is expanding, exposing new regions and species to diseases previously limited to warmer climates. Climate change not only affects the prevalence and severity of plant diseases but also influences the effectiveness of disease management strategies, necessitating adaptive approaches in agricultural practices. This review presents a thorough examination of the relationship between climate change and plant pathogens and carefully provides an analysis of the interplay between climatic shifts and disease dynamics. In addition to insights into the development of effective strategies for countering the adverse impacts of climate change on plant diseases, these insights hold significant promise for bolstering global crop production resilience against mounting environmental challenges.

**Keywords:** Climate change, Crop production, Plant diseases, Greenhouse gas emissions, mitigation strategies.

## 1. Introduction

The impact of climate change on plant diseases is substantial, exerting influence on various facets including pathogen evolution, host-pathogen interactions, and the emergence of novel pathogenic strains (Singh et al., 2023). As environmental conditions undergo alterations, pathogens undergo evolutionary shifts, adapting to novel environments and potentially giving rise to new diseases or resurfacing previously controlled ones. Concurrently, climate change can also modulate pathogen virulence (Singh et al., 2023). Climate change remains one of the most significant threats to humanity, exacting a yearly cost of approximately US$ 1.2 trillion and resulting in nearly 0.4 million fatalities annually in terms of agricultural resources (EPA, 2023). With the world's average temperature having risen by 0.74°C over the past century and atmospheric carbon dioxide ($CO_2$) concentrations escalating from 280 ppm in 1750 to 417,9 ppm in 2022, the influence on agriculture is profound (EPA, 2023). These changes significantly affect the growth and production of numerous crops on earth, simultaneously altering the severity, spread, and reproduction of several plant diseases, thereby endangering our food security (Moullec et al., 2019). In light of these climatic fluctuations and their impacts on crop plants and their phytopathogens, the imperative need for the development of new crop varieties is evident. However, this process currently takes an average of approximately 20 years (Sreenivas, 2022). The transformations witnessed carry profound implications for agricultural and ecological systems alike. The proliferation of plant diseases not only threatens crop productivity but also instigates biodiversity loss, thereby undermining crucial ecosystem services (Kashyap et al., 2018; Singh et al., 2023). Therefore, comprehending the intricacies of climate-induced shifts in plant disease dynamics becomes imperative. Such understanding forms the foundation for crafting robust strategies aiming at mitigating the adverse impacts on both agricultural sustainability and ecological integrity.

Furthermore, Many diseases that are now restricted by the need to overwinter, such as *Puccinia graminis* f. sp. *tritici*-caused wheat stem rust, can have their range expanded by rising temperatures (Singh et al., 2023). On the other hand, it was noted that *Triphragmium ulmarie*, the rust pathogen that infects *Filipendula ulmaria* (meadowsweet), was going extinct in some areas over a 30-year period during which summer temperatures rose steadily (Zhan et al., 2018). Climate projections suggest a future heightened frequency of extreme weather events, such as storms, droughts, and periods of intense heat (Cook et al., 2016), fostering diverse disease outbreaks across geographical regions. Climate-induced variations profoundly impact host susceptibility to diseases and influence the cultivation of host cultivars (Moullec et al., 2019). The onset of global warming, evident through shifts in mean temperatures, changes in annual precipitation patterns, and prolonged droughts, can disrupt plant growth and development, ultimately resulting in crop losses (Ebi et al., 2016). Environmental stresses triggered by climate change can render plants vulnerable to invasion by bacterial and fungal pathogens, thereby compromising plant health and increasing mortality rates (Devendra, 2012).

The dynamic landscape and evolving interactions between pathogens and their hosts contribute significantly to the emergence of novel disease events (Velásquez et al., 2018). Pathogenic organisms employ a variety of structures and compounds adeptly to infiltrate and manipulate host plants, triggering the onset of diseases (Ogbonna and Umunna, 2017). In response, plants activate defense mechanisms to counteract pathogen assaults (Olori-Great and Opara, 2017). A notable example of this intricate interplay is observed in the interaction between *Colletotrichum gloesporioides* and avocado fruit, where fruit-produced epicatechin acts as a defense mechanism against fungal laccase proteins (Djami-Tchatchou et al., 2013).

The evolving gene pathogenicity of pathogens across geographic regions underscores the regional influence on disease dynamics (Djami-Tchatchou et al., 2013; Grassi et al., 2009; Mayek-PÉrez et al., 2002). Abiotic stresses, such as salinity, drought, and high temperatures, play a pivotal role in molding the complex interplay between pathogens and hosts, influencing both plant defense mechanisms and pathogen virulence (Sun et al., 2021). Pathogens continuously refine their virulence mechanisms to breach host defenses and trigger disease onset (Doehlemann et al., 2017), while abiotic factors regulate plant defense mechanisms and shape pathogen dynamics across diverse ecological niches (Adhikari et al., 2013).

Understanding the nexus comprising climate change and plant diseases is imperative from both agricultural and ecological perspectives, ensuring food security and mitigating the adverse impacts of diseases on vital food crops (Chakraborty and Newton, 2011), these mitigation strategies should include the development of resistant cultivars, innovative control methods, and adaptive techniques to minimize potential losses (Hernandez Nopsa et al., 2014). Tackling the significant challenges posed by climate-driven changes in disease dynamics requires substantial investments in research and development, these efforts are aimed at fostering the growth of climate-resilient crops and enhancing disease management protocols (Desai et al., 2021). This entails the creation of cultivars with heightened disease resistance and the adoption of innovative control strategies, including biological agents and integrated disease management systems (Chakraborty and Newton, 2011). The evolving disease landscape, precipitated by climate change, underscores the urgency of advancing predictive modeling approaches to forecast the severity of major infections affecting critical crops in real-world field scenarios. Furthermore, adapting to the changing climate mandates the integration of sustainable food production strategies with robust disease control measures (Singh et al., 2023).

Therefore, this review elucidates the multifaceted drivers of climate change, encompassing greenhouse gas emissions, deforestation, and anthropogenic activities, along with their consequential impacts on environmental factors such as temperature and soil pH. Disruptions to these parameters can profoundly influence plant health, host susceptibility, disease dynamics, and pathogen virulence and dispersion.

## 2. Climate change and its drivers

Climate change stems from a complex interplay of natural phenomena and human-induced activities. Human activities, such as fossil fuel combustion, deforestation, and agriculture are also leading drivers of deforestation, especially in tropical regions. Clearing forests for agricultural land releases large amounts of carbon stored in trees into the atmosphere, while also reducing the number of trees available to absorb CO2, industrial processes and fertilizers and pesticides contribute to greenhouse gas emissions during their manufacture and application (Nda et al., 2018). Additionally, they can affect the health of ecosystems and their ability to store carbon and emit greenhouse gases into the atmosphere, thereby catalyzing global warming and subsequent climate change (Nda et al., 2018; Trenberth, 2018). The well-established scientific consensus postulates that greenhouse gas emissions directly contribute to climate change by trapping solar heat within the earth's atmosphere, leading to a plethora of environmental consequences (Kweku et al., 2019).

Human-induced greenhouse gas emissions exert a profound influence on the Earth's climate, a fact extensively corroborated by the Intergovernmental Panel on Climate Change (IPCC). The escalation in the earth's average temperature attributable to human emissions, notably of $CO_2$ and methane ($CH_4$), has precipitated an array of consequences, including perturbations to natural cycles, escalating sea levels, and exacerbation of extreme weather events (Kabir et al., 2023). On the other hand, there are also deforestation impacts extending to both local and global scales. Studies have shown that deforestation contributes to approximately 10-20% of global greenhouse gas emissions, primarily through the release of $CO_2$ into the atmosphere (Diego et al., 2010), with Indonesia and Brazil being the top emitters, accounting for approximately 80% and 70% of their emissions, respectively (Hunjan and Lore, 2020). In addition to a strong net global warming as a result of both $CO_2$ and biophysical effects particularly in the context of industrial-era deforestation, it increases the annual local average temperature by approximately 1 ºC and also affects rainfall levels (Lawrence et al., 2022).

In 1913, French physicists Henri Buisson and Charles Fabry made the ground-breaking discovery of ozone gas, an achievement later acknowledged by British meteorologist Dobson. Dobson's invention of the Dobson meter allowed for the estimation of stratospheric ozone gas from ground level. He subsequently established an international network of ozone monitoring stations, which were aptly named after him. However, in the 1970s, a concerning "hole" emerged in the stratospheric ozone layer, notably over Antarctica, and it was determined that human-made substances were primarily responsible for this phenomenon (Demers et al., 2016). The depletion of the ozone layer has sparked global concerns, with anthropogenic activities largely identified as the root cause of this issue. Specifically, the continuous rise in global temperatures and escalating concentrations of $CO_2$ are contributing to the destruction of the ozone layer. Unlike many forms of pollution stemming from various sources, the depletion of the ozone layer is primarily attributed to a specific chemical substance: chlorofluorocarbons (CFCs) (Demers et al., 2016). Growing amounts of nursery gas emissions are thought to be the main cause of the problem. The following greenhouse gases are known to have a major effect on the environment: CO2: Carbon Dioxide - CH4: Methane - N2O: Nitrous Oxide - HFC: Hydrofluorocarbons-PFC: Perfluorocarbons - SF6: Sulfur Hexafluoride (IPOC, 1995). Among these, $CO_2$ is widely considered the primary driver of global climate change. Despite the significant impact of the 2020 COVID-19 pandemic and associated lockdown measures on energy consumption, $CO_2$ emissions, production activities, and daily life, $CO_2$ levels in the troposphere continue to fluctuate both temporally and spatially. This gas is generated by both natural and anthropogenic processes, and its concentration has surged by 25% over the past 125 years (Kabir et al., 2023).

Amidst these critical times, concerns about climate change are rapidly escalating, as evidenced by individuals' self-reported negative emotional responses to the awareness of its significance (Clayton and Karazsia, 2020). Human industrial activities, especially since the Industrial Revolution, have significantly elevated atmospheric $CO_2$ levels, the main aspect of climate change is listed in (**Table 1**). Strikingly, the concentration of $CO_2$ in the stratosphere has surged by 30-31% over the past three decades, soaring from 280 ppm in 1750 to 400 ppm in 2013 (Diallo et al., 2017). This unprecedented increase has disrupted the relatively stable $CO_2$ levels maintained for almost a millennium (Kabir et al., 2023).

**Table 1**. Evolution of climate change aspects over the past 20 years.

| Aspect | 2000 | 2005 | 2010 | 2015 | 2020 | Reference |
|---|---|---|---|---|---|---|
| **Global average temperature (°C)** | 14.6 | 14.66 | 14.70 | 14.84 | 14.9 | Berkeley Earth, 2024 |
| **$CO_2$ concentration (ppm)** | 368 | 380 | 390 | 403 | 413 | Oceanography, 2023 |
| **Sea level rise (mm $year^{-1}$)** | 2.8 | 3.1 | 3.4 | 3.6 | 3.7 | European Service, 2018 |
| **Average global ocean pH** | 8.14 | 8.12 | 8.10 | 8.08 | 8.06 | Jiang et al., 2023<br>Sutton et al., 2019 |

## 3. Impact of climate change on plant diseases

### *3.1. Temperature*

Temperature stands as a paramount environmental determinant influencing plant growth, development, and physiological processes, alongside shaping the life cycle, distribution, and virulence of plant pathogens (Hunjan and Lore, 2020). Additionally, temperature governs critical aspects of the pathogen infection process, including its rate, duration, latency period, sporulation, dispersal of inoculum, and host resistance dynamics (Kweku et al., 2019). Generally, elevated temperatures foster the proliferation and propagation of plant pathogens, notably fungi, and bacteria, while concurrently compromising host defense mechanisms (Devi et al., 2022). However, it's crucial to note that the optimal temperature range for pathogen-host systems can vary, with some pathogens exhibiting susceptibility to extremes of heat or cold (Porras et al., 2023).

The escalation in global mean temperatures resulting from climate change exerts significant consequences on plant diseases (Chaloner et al., 2021). For instance, temperature increases may precipitate shifts in agroclimatic zones, prompting host plant migration and facilitating the emergence of novel disease complexes (Hunjan and Lore, 2020). Warming trends may also bolster the overwintering and persistence of pathogens and vectors, such as insects and nematodes, thereby prolonging their activity periods and expanding their geographic ranges (El-Sayed and Kamel, 2020). Furthermore, climate-induced alterations in host plant phenology and physiology can render them more susceptible or resistant to specific pathogens (Pathak et al., 2018). Empirical evidence suggests that heightened temperatures can exacerbate the intensity of various crop diseases, including wheat rust (*Puccinia triticina*), rice blast (*Magnaporthe grisea*), potato late blight (*P. infestans*), and citrus canker (*Xanthomonas* spp.) (Ahmed et al., 2024; Charaya et al., 2021; Singh et al., 2023).

### *3.2. Precipitation*

Precipitation stands as a critical environmental factor influencing plant diseases by shaping water and nutrient availability, soil moisture, pH levels, pesticide leaching, runoff, and inoculum formation and dissemination (Chen et al., 2023). Moreover, precipitation plays a pivotal role in determining the duration of leaf wetness, a crucial factor affecting the infection and sporulation of numerous foliar pathogens (Beyer et al., 2022; Dutta et al., 2020). In general, heightened precipitation tends to promote the development and spread of plant diseases, particularly those caused by fungi and oomycetes, while simultaneously diminishing the effectiveness of chemical and biological control measures (Lim et al., 2023). However, the impact of precipitation on plant diseases can vary depending on factors such as timing, frequency, intensity, and form of precipitation, as well as its interaction with other climatic variables like temperature and humidity (Skendžić et al., 2021).

The change in precipitation patterns due to climate change has diverse effects on plant diseases (Garrett et al., 2021). For instance, increased rainfall may enhance the occurrence and severity of soil-borne and foliar diseases, such as root rot, damping-off, leaf spot, and blight (Lamichhane et al., 2023). Increased rainfall may also increase the risk of flooding and waterlogging, which can create anaerobic conditions and favor the development of some pathogens, such as *Pythium* spp. and *Phytophthora* spp. (Martínez‐Arias et al., 2022). On the other hand, decreased rainfall may reduce the incidence and spread of some diseases, such as downy mildew and powdery mildew (PM), but may also increase the susceptibility of host plants to drought stress and other pathogens, such as *Fusarium* spp. and *Verticillium* spp. (Maurya et al., 2022). Moreover, decreased rainfall may increase the reliance on irrigation, which can create favorable conditions for some diseases, such as bacterial wilt caused by *Erwinia tracheiphila* and root-knot nematode caused by *Meloidogyne* spp. (Erayya et al., 2023).

### *3.3. Humidity*

Humidity serves as another critical environmental factor impacting plant diseases, influencing key processes such as evapotranspiration, transpiration, and stomatal conductance in host plants, as well as the germination, infection, and survival of plant pathogens (Dixit et al., 2023). Additionally, humidity plays a significant role in the formation and deposition of dew, serving as a source of free water for many pathogens (Nath, 2021). In general, elevated humidity levels tend to foster the development and spread of plant diseases, particularly those caused by fungi and bacteria, while also diminishing the effectiveness of host resistance mechanisms and control measures (Lim et al., 2023). However, the impact of humidity on plant diseases can vary depending on factors such as the type and stage of the pathogen, the host plant, and its interaction with other climatic variables like temperature and precipitation (Dixit et al., 2023).

The change in humidity levels due to climate change is expected to have significant impacts on plant diseases. For instance, increased humidity may enhance the occurrence and severity of foliar and fruit diseases, such as anthracnose (*Colletotrichum* spp.), scab (*Streptomyces scabies*), and gray mold (*Botrytis cinerea*) (Ji et al., 2021; Maurya et al., 2022). Increased humidity may also increase the risk of post-harvest diseases, such as gray mold (*B. cinerea*) and soft rot (*Pandanus conoideus*), which can cause significant losses in storage and transportation (Moradinezhad and Ranjbar, 2023). On the other hand, decreased humidity may reduce the incidence and spread of some diseases, such as rust and smut, but may also increase the susceptibility of host plants to water stress and other pathogens, such as wilt and canker (Jeger, 2022). Moreover, decreased humidity may affect the quality and quantity of pollen and nectar, which can affect the pollination and reproduction of host plants (Biella et al., 2022).

### 3.4. Extreme weather events

Extreme weather events represent a significant environmental factor impacting plant diseases, leading to physical damage, physiological stress, and biochemical alterations in host plants, as well as altering the population dynamics and diversity of plant pathogens and their vectors (Singh et al., 2023). These events encompass storms, heat waves, cold snaps, and hail, which are experiencing increased frequency and intensity due to climate change (Faranda et al., 2022). Typically, extreme weather events heighten the vulnerability and susceptibility of host plants to diseases, thereby reducing the efficacy of control measures (Gullino et al., 2022). For instance, storms can inflict physical wounds on host plants, serving as entry points for pathogens like fire blight and crown gall (Hong et al., 2021), and disperse rust and aphid vectors (Bastas, 2022). Heat waves and cold snaps may induce heat and oxidative stress in plants, compromising their photosynthesis and respiration and rendering them more susceptible to pathogens such as PM, leaf spot, and black rot (Rivero et al., 2022; Tanveer et al., 2023). Furthermore, hail damage to protective structures like the cuticle and epidermis can increase plant susceptibility to diseases like downy mildew and bacterial spot (Khadiri et al., 2023).

### 3.5. Solar radiation and wind

Climate change has altered various non-temperature related environmental factors such as solar radiation and wind, which significantly influence plant ecosystems. For instance, increased global radiation has been noted since the 1990s, particularly affecting photosynthesis in primary producers during spring at Lake Taihu, China, this has led to variations in the phytoplankton communities, which are crucial to aquatic ecosystems. The combination of these changes with elevated nutrient levels due to higher rainfall and runoff contributes to more severe algal blooms, highlighting the complex interplay of climate change factors on aquatic life (Deng et al., 2018). Solar radiation can affect the development and spread of plant diseases. For instance, it can impact the survival of fungal spores on plant surfaces (Bornman et al., 2015). Solar radiation can influence the survival and growth of plant pathogens. Exposure to sunlight can lead to the inactivation of certain pathogens due to UV radiation (Campillo et al., 2012). For example, *Cercospora* leaf spot, a severe leaf blight of beets, and gray mold (*Botrytis cinerea*) on strawberries have been suppressed by UV light exposure (Kumari et al., 2017)

Additionally, changes in wind patterns affect the sediment dynamics in lakes, influencing light penetration and nutrient distribution, which are vital for aquatic plant growth. The decrease in wind speed, coupled with increased cloud cover, can reduce solar radiation availability, leading to light limitation. These factors collectively enhance the likelihood of plant pathogen outbreaks by creating favorable conditions for their growth and spread, demonstrating the broader ecological impacts of climate change on plant health (Deng et al., 2018). Wind can play a role in dispersing plant pathogens over long distances, aiding in the spread of diseases between plants and regions, Strong winds can physically damage plants, creating entry points for pathogens to infect the plant tissues (Krafft et al., 2019). Fungi that produce spores on aerial parts of plants, such as leaves or flowers, can be easily dispersed by wind over a wide range of distances. Examples include powdery mildews and rust fungi that infect cereal (El Jarroudi et al., 2020). Dry, lightweight spores or propagules are more easily carried by wind compared to wet, heavy ones. Pathogens such as *Xanthomonas axonopodis* pv. *citri* (citrus canker) rely on wind dispersal of dry inoculum (Esker et al., 2007). Long-distance wind dispersal can spread pathogens across and even between continents, reestablishing diseases in areas where host plants are seasonally absent. This can lead to founder effects where atypical pathogen genotypes cause epidemics (Rieux et al., 2014).

A study by Myers et al. (2021) explored how climate change could increase the spread of plant pathogens, focusing on fungal and oomycete pathogens. These organisms, which cause significant crop losses, are likely to spread further as global temperatures rise, potentially affecting higher latitude regions previously less susceptible to such pathogens. The research incorporated various climate models to predict shifts in crop yields and pathogen spread, indicating an overall increase in pathogen activity with warming temperatures, which could counteract gains in agricultural productivity due to climate change (Myers et al., 2021).

## 4. Changes in plant pathogens

Climate change poses a direct threat to global food security, impacting crop physiology and productivity, as well as exerting an indirect influence on plant-associated microbiota, which includes plant pathogens. Although the interactions among host plants, pathogens, and environmental factors can be intricate, recent research is starting to reveal certain overarching patterns in how plant diseases will impact future crop production (Raza and Bebber, 2022). These shifts will profoundly affect the growth and cultivation of various crops on Earth.

Concurrently, they will influence the reproduction, spread, and severity of numerous plant pathogens, posing a significant threat to global food security (Gautam et al., 2013).

Plant disease outbreaks pose a significant threat to global food security and environmental sustainability, undermining primary productivity and biodiversity on a global scale. Climate change further exacerbates these risks by shaping pathogen evolution and altering host-pathogen interactions, thereby fostering the emergence of novel pathogenic strains (Singh et al., 2023). Over the past decade, the impact of climate change on plant diseases has been subject to extensive investigation (Yáñez-López et al., 2012). The anticipated shifts in climate are certain to influence pathogen development and survival rates, alongside altering host susceptibility, resulting in variations in disease impact on crops. The nuanced effects of climatic alterations will vary based on the specific pathosystem and geographical context, influencing ideal infection conditions, host specificity, and infection mechanisms (Elad and Pertot, 2014). Furthermore, alterations in abiotic conditions will inevitably reshape the microclimate enveloping plants, potentially disrupting the beneficial effects of soil microbial communities and canopy pathosystems. These simultaneous impacts on pathogens and host plants are anticipated to induce significant shifts in disease manifestation, geographical distribution, and economic implications, thus demanding adaptations in disease management strategies and cropping systems  (Elad and Pertot, 2014). Importantly, despite potential gains in crop yields resulting from climate change, plant diseases can offset such advancements (Raza and Bebber, 2022). The influence of climate on plant diseases is profound, as it shapes host plants, vector behavior, and mechanisms of pathogen dispersal, thereby influencing the likelihood of pathogen invasions.

Human decisions significantly influence economically substantial pathogen invasions, as landscape connectivity for pathogen movement is influenced by the spatial arrangement of hosts, pathogens, and environmental conditions (Garrett et al., 2014). Consequently, assessing limiting factors before invasion becomes challenging, highlighting the critical role of proactive management strategies in mitigating the impacts of climate-induced shifts in plant disease dynamics. The impact of drought conditions on plant diseases is complex and carries substantial implications for global agriculture. Traditionally, drought has been viewed as inhibiting or disturbing the development of diseases caused by pathogens that thrive in moist environments. However, it's important to note that certain diseases can benefit from drought conditions, as stressed plants become more susceptible to specific pathogens. This multifaceted relationship underscores the need for a nuanced understanding of how drought affects disease dynamics in agricultural systems (Wegulo et al., 2013). As anticipated climate change is expected to elevate the occurrence and duration of drought in various regions globally. Therefore, it is crucial to understand how these shifts will impact plant-pathogen interactions. This shift may impact the natural lifecycles of plant pathogens, influence host susceptibility to infection or disease manifestation, alter the natural distribution of pathogens, and modify the pace of genetic changes within pathogen populations. Cumulatively, these effects are likely to have repercussions on diverse pathosystems, holding economic significance for productive sectors (Wakelin et al., 2018). Charcoal rot, also known as dry-weather wilt, is caused by the fungus *Macrophomina phaseolina* and can impact a variety of crops, including corn, sorghum, soybean, sunflowers, and dry beans. The fungus has a broad distribution and infects a wide range of hosts. It forms microsclerotia, hardened fungal survival bodies, inside infected crop tissue. These microsclerotia serve as a means for the fungus to overwinter in infested crop debris and soil. While they can survive for several years in dry soil, their survival is limited to a few weeks in wet, saturated soils. Given that most rotations include hosts susceptible to this fungus annually, there is a high potential for the pathogen to be present in numerous fields, and dry conditions further favor its prevalence. *Aspergillus* ear rot poses a significant threat in fields affected by drought and lacking irrigation. This disease is notable due to the fungal species responsible, typically *Aspergillus flavus* and *A. parasiticus*, which have the potential to produce aflatoxin. Aflatoxin, found in contaminated grain, poses serious health risks to both animal and human consumers. Meanwhile, *Fusarium* pathogens, which persist in soil and crop residues, are notorious for causing diseases influenced by numerous factors. Among these factors, plant stress particularly drought plays a significant role in increasing the incidence and severity of *Fusarium*-related diseases. *Fusarium* species are notorious for causing substantial yield losses in crops such as corn, wheat, and soybean, with drought exacerbating the impact of these diseases. For instance, *Fusarium verticillioides* can lead to substantial yield losses and mycotoxin contamination in corn, affecting stalk rot, ear rot, and kernel rot. Wheat root diseases, such as common root rot (*Bipolaris sorokiniana*) and *Fusarium* crown rot (*Fusarium* spp.), are exacerbated in dry conditions, causing severe yield reduction from early root infections. Interestingly, drought has been observed to reduce the likelihood of sudden death syndrome in soybeans, while simultaneously promoting other *Fusarium* infections that result in *Fusarium* wilt (Wegulo et al., 2013). Assessments have been conducted to evaluate the potential impact of drought on several plant diseases significant to New Zealand. These include pea root rot (caused by *Aphanomyces euteiches*), onion white rot (*Sclerotium cepivorum*), wheat take-all (*Gaeumannomyces graminis* var. *tritici*), wheat crown rot (*Fusarium* spp.), *Brassica* blackleg (*Leptosphaeria maculans*), grapevine black foot (*Ilyonectria/Dactylonectria* spp.), kiwifruit *Sclerotinia* rot (*Sclerotinia sclerotiorum*), and Radiata pine red needle cast (*Phytophthora pluvialis*). In most pathosystems, an anticipated outcome of increased drought is an elevation in disease expression. However, for certain diseases, such as *Sclerotinia* rot in kiwifruit and red needle cast in Radiata pine, drought may lead to a reduction in disease severity (Wakelin et al., 2018).

Elevated levels of $CO_2$ and temperature are known to instigate complex repercussions on plant pathogens (Gullino et al., 2018). The escalation in temperatures and augmented concentrations of $CO_2$ linked with climate change are expected to profoundly influence the interplay between plants and diseases. Climate exerts a pivotal influence on the occurrence, as well as the temporal and spatial distribution, of plant diseases. In polar-ward agroclimatic zones, climate change is likely to induce a modification resulting in a shift in the geographic distribution of host pathogens (Yáñez-López et al., 2012).

In the face of rising temperatures and increased atmospheric $CO_2$ levels, new pathogen strains may undergo rapid evolution. This evolutionary process is fueled by a notable increase in pathogen populations, leading to heightened proliferation and infection cycles within an expanded canopy, supported by favorable microclimatic conditions. Moreover, changes in geographic distribution may bring together diverse pathogen lineages or genotypes that may not typically share the same ecological niche, potentially leading to an escalation in pathogen diversity (Chakraborty, 2013).

The evolving climate, coupled with the concurrent rise in atmospheric $CO_2$ levels, holds the potential to significantly impact the severity of plant diseases, posing a looming threat to future crop yields (Zhou et al., 2019). These anticipated shifts emphasize the critical importance of comprehensive research initiatives aimed at unraveling the intricate dynamics between climate change and plant-pathogen interactions. Such efforts are essential for developing effective strategies to mitigate the adverse effects of climate change on agricultural productivity and ensure global food security in the face of evolving climatic challenges.

Elevated temperatures associated with climate change often exacerbate the severity of plant diseases (**Figure 1**). Understanding how plants respond to pathogens under high-temperature stress is crucial for enhancing crop resilience. However, the molecular mechanisms governing this response remain largely unexplored (Cohen and Leach, 2020). The resistance of crops to stem rust, particularly Sr31, is compromised by the Ug99 race of stem rust caused by

*P. graminis* f. sp. *tritici*. Furthermore, elevated temperatures and increased $CO_2$ levels heighten the threat of late blight (*P. infestans*) in potatoes, as well as significant rice diseases including blast (*P. oryzae*) and ShB (*R. solani*) (Gautam et al., 2013).

Research is underway to investigate the impact of climate warming on *Phytophthora cinnamomi*, a widespread and highly destructive forest pathogen. In Europe, the winter survival of this pathogen significantly influences the development of the disease in oak trees, particularly in *Quercus robur* and *Q. rubra*. The research compares the potential geographic ranges of the pathogen and its associated disease in France over two distinct periods: 1968–1998 and 2070–2099. Simulations incorporate a physiologically based approach to predict the pathogen's winter survival relative to microhabitat temperature (specifically, in the phloem of infected trees), along with a regionalized climatic scenario derived from a global circulation model. Projections indicate that positive anomalies in winter temperatures are expected to vary between 0.5–5.1°C during the period 2070–2099 compared to 1968–1998, with variations observed across sites and months. Consequently, higher annual rates of *P. cinnamomi* survival are anticipated, potentially leading to an eastward expansion of the disease's range from the Atlantic coast by one to a few hundred kilometers within a century (Bergot et al., 2004). These findings underscore the critical importance of comprehending the intricate interactions between climate change and plant-pathogen dynamics. Advancing our understanding in this domain is imperative for devising effective strategies to alleviate the impact of climate change on agricultural productivity and ensure global food security amidst evolving environmental challenges. The outcomes of research investigating the effects of climate change on various pathosystems, such as those affecting grapevines, including downy and powdery mildew, as well as several pathogens targeting vegetable crops like rocket, basil, beet, and zucchini, have been demonstrated. Elevating both $CO_2$ levels and temperature resulted in an increased occurrence of PM on zucchini, *Alternaria* leaf spot on rocket salad, black spot, and downy mildew on basil, *Allophoma tropica* on lettuce, and Phoma leaf spot on garden beet. Conversely, variable effects were noted when individual climate parameters were considered separately. The impact of altered environmental conditions on certain physiological parameters affecting mycotoxin production and disease management in selected pathosystems was also explored. It was observed that $CO_2$ concentration and temperature exerted distinct influences on disease severity and mycotoxin production. Regarding the application of biocontrol agents, the effectiveness of *Ampelomyces quisqualis* against zucchini powdery mildew was found to be enhanced under elevated temperature and $CO_2$ conditions (Gullino et al., 2018).

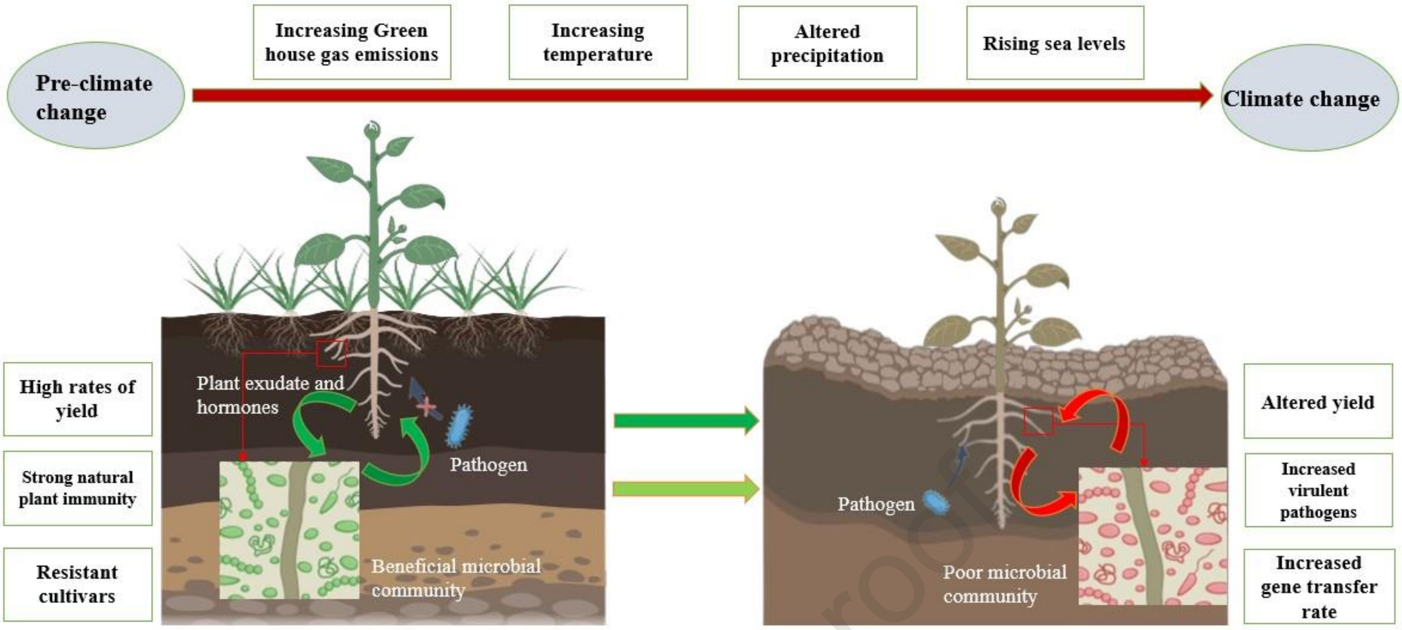

**Figure 1.** Impact of climate change on plant-pathogen interactions

ShB, caused by *R. solani*, poses a significant threat to rice (*Oryza sativa* L.) production. However, the response of rice ShB risk to elevated $CO_2$ ($ECO_2$) and temperature in the context of future climate change remains unclear. Field experiments were conducted with inoculated *R. solani*, considering two $CO_2$ levels (ambient and enriched up to 590 mmol $mol^{-1}$) and two temperature levels (ambient and increased by 2.0°C) using a free-air $CO_2$ enrichment (T-FACE) system for two cultivars, namely a susceptible cultivar (Lemont) and a resistant cultivar (YSBR1). Results revealed that, upon inoculation with *R. solani*, the vertical length of ShB lesions for cv. Lemont was significantly longer than that for cv. YSBR1 across the four $CO_2$ and temperature treatments. Elevated temperature significantly increased the vertical length of ShB lesions, while $ECO_2$ had no such effect for both cultivars. Under the combination of $ECO_2$ and elevated temperature, the vertical length of ShB lesions increased by 21–38% for cv. Lemont and by -1–6% for cv. YSBR1. The significant increase in membrane lipid peroxidation level was associated with a notable rise in the vertical length of ShB lesions under the combination of $ECO_2$ and elevated temperature. The $ECO_2$ was unable to offset the adverse effect of elevated temperature on the yield of both cultivars under future climate change. Rice yield and biomass experienced a further decline by 2.0–2.5% and 2.9–4.2%, respectively, due to an increase in ShB severity under the combination of $ECO_2$ and elevated temperature. Therefore, it is imperative to implement rational agronomic management practices aimed at enhancing resistance to ShB disease and improving grain yield for rice under future climate change conditions (Shen et al., 2023). Comparisons were made between the responses of the model plant *Arabidopsis thaliana* to leaf and root pathogens employing hemi-biotrophic or necrotrophic infection strategies under pre-industrial, current, and projected future atmospheric $CO_2$ conditions. Under $ECO_2$ conditions, plants exhibited increased resistance to the necrotrophic leaf pathogen *B. cinerea*, but a reduction in resistance to the hemibiotrophic leaf pathogen *Pseudomonas syringae* pv. *tomato* was observed. Conversely, plants grown under low $CO_2$ displayed the opposite pattern. Disease severity induced by the soil-borne pathogens *Fusarium oxysporum* f.sp. *raphani* and *R. solani* remained similar across all tested $CO_2$ conditions. The findings emphasize that atmospheric $CO_2$ levels influence the equilibrium between salicylic acid- and jasmonic acid-dependent defenses, consequently affecting the resistance against foliar hemibiotrophic and necrotrophic pathogens (Zhou et al., 2019). The $CO_2$ serves as a significant sensory cue for various animals, encompassing both parasitic and free-living nematodes. The behavioral reactions of nematodes to $CO_2$ are often context-dependent, experience-dependent, or life stage-dependent, indicating the vital roles $CO_2$ plays across multiple ethological contexts throughout the nematode life cycle. Additionally, nematodes exhibit diverse physiological responses to $CO_2$ (Banerjee and Hallem, 2020). Concurrently, the interplay of $ECO_2$ levels, temperature shifts, and altered precipitation strongly influences the biology of nematodes, including those parasitizing plants and insects. While nematode development tends to accelerate in warmer soil temperatures induced by climate change, the precise implications of these climate change effects on nematode biology and the overall plant-nematode interaction continuum are not yet fully understood (Dutta et al., 2023).

## 5. Host-pathogen interactions

Global climate change exerts significant impacts on plant ecosystems by altering key environmental factors. Factors such as temperature, precipitation, sunlight duration and quality, and nutrient availability (e.g. nitrogen, phosphorus, potassium) are pivotal in determining plant growth and are anticipated to change because of global climate change. $ECO_2$ levels resulting from climate change can enhance plant growth by stimulating increased photosynthesis, albeit at the cost of reduced evaporative cooling (Dutta et al., 2023).

The influence of climate change on pests and pathogens primarily operates through plants. $ECO_2$ levels, rising temperatures, and shifts in precipitation patterns disrupt plant growth and development, leading to alterations in canopy architecture, size, density, microclimate, and the amount of susceptible tissue. These changes in host physiology and canopy microclimate, particularly under $ECO_2$ levels, affect the production, dispersal, and survival of pathogen inoculum, as well as the feeding behavior of insect pests. Increased temperatures accelerate plant growth and development, thereby reshaping canopy architecture and influencing the development of pests and pathogens. Moreover, changes in precipitation patterns, whether resulting in drought or flooding stress, impact canopy architecture and have corresponding effects on pests and pathogens. Despite the profound interactions occurring at the canopy level, they are frequently overlooked in epidemiology models used to forecast the impacts of climate change (Pangga et al., 2013).

Temperature variations affect both the host and the pathogen, necessitating risk analyses for each pathosystem to understand the implications of climate change (Yáñez-López et al., 2012). Observational studies consistently highlight increasing temperatures as the predominant factor driving the impact of diseases. Process-based models indicate that rising temperatures could result in shifts in disease pressure along latitudinal lines while drying conditions might alleviate disease risks (Raza and Bebber 2022).

$ECO_2$, a key factor in climate change, is recognized for its ability to modify various plant processes (**Figure 2**), including physiology, growth, and resistance to pathogens (Sanchez-Luca et al., 2023). Human activities have led to a doubling of $CO_2$ concentrations since the Industrial Revolution. While this increase could potentially enhance plant growth through the '$CO_2$ fertilization' effect, recent studies present conflicting findings regarding the impacts of $ECO_2$ on plant-pathogen interactions (Smith and Luna, 2023). While studies conducted under controlled conditions have identified the effects of $ECO_2$ levels, field responses, such as the adaptation of pathogens over time, may differ (Yáñez-López et al., 2012). Experimental studies propose that the elevation of atmospheric $CO_2$ levels could intensify the impact of diseases (Raza and Bebber, 2022). $ECO_2$ and the accompanying climate changes carry the potential to expedite the evolution of plant pathogens, subsequently influencing their virulence. The interactions between plants and pathogens in the context of $ECO_2$ can significantly disrupt both agricultural and natural systems. However, the existence of a fundamental knowledge gap arises from the scarcity of experimental data, hindering our ability to accurately predict future outcomes in this regard. In the absence of information regarding crop species, a study demonstrated an increase in the aggressiveness of the plant pathogen (*Erysiphe cichoracearum*) under $ECO_2$. Concurrently, alterations in the leaf epidermal characteristics of the model plant *Arabidopsis thaliana* L. are observed. Stomatal density, guard cell length, and trichome numbers on leaves that develop post-infection show an increase under $ECO_2$, contrasting with the responses in non-infected conditions. Given that many plant pathogens rely on epidermal features for successful infection, these responses create a positive feedback mechanism, enhancing the susceptibility of newly developed leaves to further pathogen attacks. Additionally, an analysis of resistant and susceptible ecotypes suggests inherent differences in epidermal responses to $ECO_2$ (Lake and Wade, 2009).

Wheat diseases represent a persistent and evolving threat to global food security, yet there remains limited understanding of how $ECO_2$ levels will impact these diseases, consequently affecting grain supply security. With atmospheric $CO_2$ surpassing the 400 ppmv benchmark in 2013 and expected to double or triple by the end of the century, a study delved into the influence of both pathogen and wheat acclimation to $ECO_2$ on the development of *Fusarium* head blight (FHB) and *Septoria tritici* blotch (STB) diseases in wheat. The study involved cultivating plants and pathogens under either 390 or 780 ppmv $CO_2$ for two wheat generations and multiple pathogen sub-cultures, followed by standard disease trials. The acclimation of pathogens and the wheat cultivar Remus to $ECO_2$ resulted in increased severity for both STB and FHB diseases compared to ambient conditions, with a more pronounced effect observed for FHB. The highest FHB disease levels and associated yield losses occurred when both the pathogen and wheat were acclimated to $ECO_2$. Similarly, experiments conducted with the disease-resistant cultivar CM82036 revealed that pathogen acclimation significantly increased disease levels and yield loss under $ECO_2$ conditions, indicating diminished effectiveness of the innate defense pathways in this wheat cultivar. In conclusion, the study highlights that acclimation to $ECO_2$ in the coming decades will significantly shape the outcomes of plant-pathogen interactions and impact the durability of disease resistance (Váry et al., 2015).

The impact of $ECO_2$ on the foliar fungal pathogen *Phyllosticta minima*, affecting *Acer rubrum* in the understory at the Duke Forest free-air $CO_2$ enrichment experiment in Durham, North Carolina, has been investigated. Surveys conducted in the 6th, 7th, and 8th years of $CO_2$ exposure revealed a significant reduction in disease incidence under $ECO_2$. There were 22%, 27%, and 8% fewer saplings affected and 14%, 4%, and 5% fewer infected leaves per plant in the three consecutive years, respectively. $ECO_2$ also led to a notable decrease in disease severity across all years, with mean lesion area reduced by 35%, 50%, and 10% in 2002, 2003, and 2004, respectively. To understand the mechanisms behind these changes, comprehensive bag analyses of leaf structure, physiology, and chemistry were combined with growth chamber studies on *P. minima* growth and host infection. In vitro, exponential growth rates of *P. minima* increased by 17% under $ECO_2$, discounting the possibility that disease reductions were due to direct negative effects of $ECO_2$ on fungal performance. Scanning electron micrographs confirmed that conidia germ tubes of *P. minima* enter *A. rubrum* leaves through the stomata. Although stomatal size and density remained unchanged, stomatal conductance decreased by 21–36% under $ECO_2$, resulting in smaller openings for infecting germ tubes. Reduced disease severity under $ECO_2$ was likely attributed to altered leaf chemistry and reduced nutritive quality. $ECO_2$ led to a 20% reduction in leaf N and a 20% increase in the C: N ratio, along with a 15% increase in total phenolics and a 14% increase in tannins. The described dual mechanism involves reduced stomatal opening and altered leaf chemistry, resulting in decreased disease incidence and severity under $ECO_2$, which implies a common occurrence in plant pathosystems where the pathogen targets the stomata (McElrone et al., 2005).

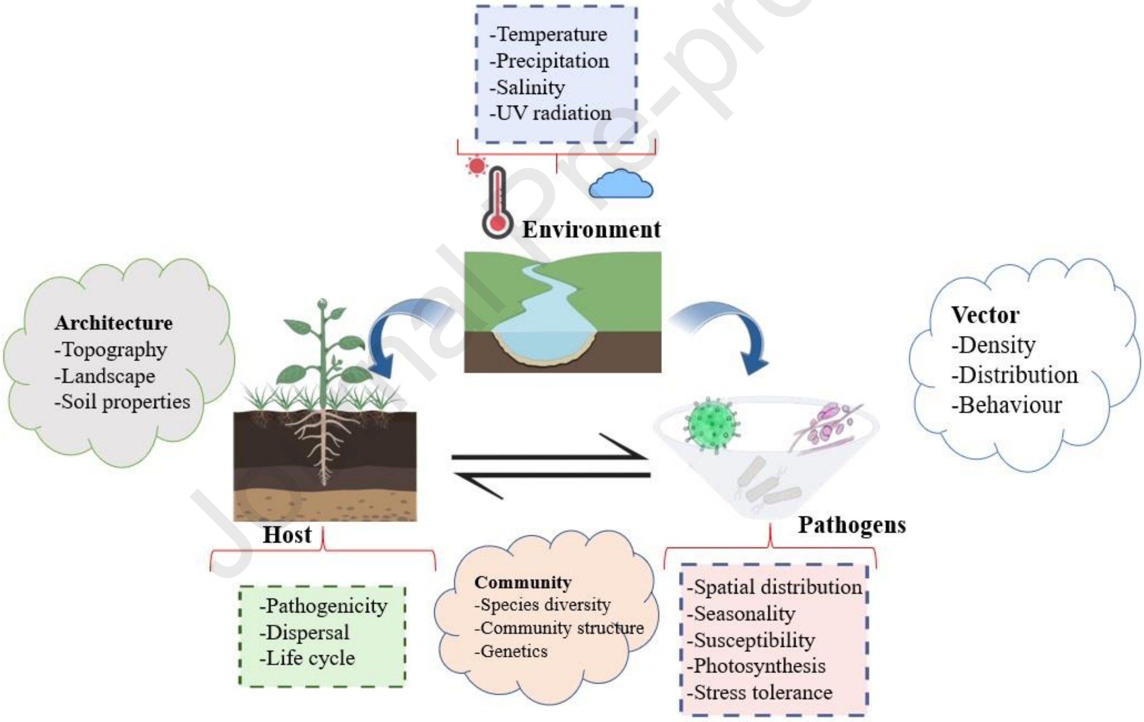

**Figure 2.** Effect of climate change factors affecting host plants, plant pathogens, and the interaction between them.

In tree species crucial in many forest regeneration strategies, *Quercus robur* is particularly susceptible to PM (Powdery mildew) disease during the seedling stage. PM is widespread in oak forests and is considered a hindrance to oak woodland regeneration. In a study aiming to elucidate the impact of $ECO_2$ on plant responses to PM, oak seedlings were cultivated in controlled environments under ambient ($aCO_2$, ~ 400 ppm) and $ECO_2$ (~ 1000 ppm) conditions and were infected with *Erysiphe alphitoides*, the causative agent of oak PM. The study monitored plant growth, physiological parameters, and disease progression. Additionally, to assess the effect of $ECO_2$ on induced resistance (IR), these parameters were evaluated following treatments with the IR elicitor β-aminobutyric acid (BABA). The results indicated that $ECO_2$ enhanced photosynthetic rates and aboveground growth but, conversely, reduced root length. Importantly, seedlings under $ECO_2$ exhibited increased susceptibility to PM. While treatments with BABA protected PM, this effect was less pronounced under $ECO_2$. Furthermore, regardless of $CO_2$ concentration, BABA did not significantly alter aboveground growth but did result in longer root systems, mitigating the impact of $ECO_2$ on root shortening. These findings underscore the influence of $ECO_2$ on plant physiology, growth, and defense, emphasizing the need for further biomolecular studies to unravel the mechanisms by which $ECO_2$ heightens oak seedling susceptibility to PM (Sanchez-Luca et al., 2023).

A study examined the impact of rising atmospheric $CO_2$ concentrations on beneficial soil fauna, specifically entomopathogenic nematodes (EPNs). The objective was to understand the influence of $ECO_2$ on the growth of maize plants (*Zea mays* L.), including root morphology, and to assess the effectiveness of the entomopathogenic nematode *Heterorhabditis bacteriophora* in this altered environment. Plants cultivated under $ECO_2$ exhibited accelerated, lengthier, denser, and larger root systems compared to those grown under $aCO_2$ conditions. Consequently, the enhanced root development resulted in reduced effectiveness of EPNs. Despite no notable disparity in host mortality between $aCO_2$ and $ECO_2$ conditions, a significantly higher number of nematodes were recovered from hosts situated near plants grown in the $aCO_2$ environment. The structural equation model analysis unveiled that this impact was indirect and mediated by the heightened morphological traits of the roots. This research represents the initial instance demonstrating how alterations in atmospheric $CO_2$ levels indirectly diminish the efficacy of globally employed entomopathogenic nematodes (EPN) for crop protection. While additional factors, such as plant volatile emissions, might influence or intensify these patterns, the results indicate that changes in root traits under $ECO_2$ negatively affect EPN effectiveness, consequently impacting the management of soil-dwelling insect pests (Hiltpold et al., 2020).

## 6. Mitigation and adaptation strategies

Management strategies for diseases hinge on prevailing climatic conditions, and any alterations in climate will inevitably trigger shifts in the spatial and temporal distribution of diseases. Consequently, control methodologies will necessitate adjustments in response to diverse climate change scenarios. In recent years, there has been a heightened emphasis on adaptation measures, largely driven by a greater certainty regarding the manifestation of several anticipated climate change scenarios. This intensified focus is warranted by the crucial role of developing highly effective strategies to acclimate plants to the challenges presented by climate change, as both productivity and food security hinge on these efforts (Gitz et al., 2016). According to the IPCC, adaptation strategies entail making modifications in natural or human systems to respond to actual or anticipated climate stimuli or their effects, to mitigate harm, or to capitalize on advantageous opportunities (IPCC, 2007). With climate change advancing and global trade accelerating, uncertainties and the frequency of both existing and new pest occurrences are poised to escalate. Consequently, bolstering the capacity for swift adaptation to disruptions and climate shifts will be increasingly paramount (Barzman et al., 2015).

Traditional management systems, notably chemical control using synthetic pesticides, remain vital in the fight against these diseases due to their immediate efficacy. However, this method brings about escalating environmental concerns, public health hazards, and the emergence of pesticide resistance. In parallel, cultural control measures such as crop rotation, intercropping, and the cultivation of resistant varieties play pivotal roles in promoting sustainable crop health. For instance, crop rotation disrupts the life cycles of pathogens and pests, while the adoption of resistant varieties reduces dependence on chemical interventions. Furthermore, biological control methods, employing environmentally friendly agents like bacteria and yeasts, are emerging as promising strategies to balance control effectiveness with the preservation of agricultural ecosystems. By integrating these diverse approaches within an integrated disease management (IDM) framework, crops can be bolstered against evolving challenges while mitigating adverse impacts on the environment and human health (Altieri and Nicholls, 2017; Khursheed et al., 2022).

In the context of climatic crisis, the conventional paradigms of crop protection, notably relying on pesticide application, witness a discernible decline in efficacy. This decline is notably attributed to the escalation of temperatures and the modulation of precipitation patterns, significantly impacting the persistence, volatilization, and overarching efficiency of these chemical interventions. Furthermore, within the realm of biological control, the intricate interplay of temperature and humidity fluctuations exerts notable influences on the reproductive cycles and overall viability of biological control agents. Meanwhile, the migratory patterns of pests to novel geographical zones pose a formidable challenge, potentially surpassing the establishment rate of their natural adversaries (Deguine et al., 2021; Kumar et al., 2023).

IDM stands as a holistic and strategic approach to safeguarding plant health, blending diverse methods for economically feasible and environmentally sound disease control. Anchored in a deep comprehension of disease biology, IDM entails monitoring vigilant disease, leveraging forecasting models, and prioritizing preventive measures like crop rotation and the adoption of resistant varieties. Moreover, this methodology seamlessly incorporates biological, chemical, and physical controls to manage diseases effectively while curbing environmental repercussions. In the era of climate change, IDM necessitates adaptive measures, encompassing the refinement of risk assessment models, the development of climate-resilient crop varieties, and the enhancement of biological control agent efficacy. Advancements in irrigation systems and the integration of cutting-edge technologies such as remote sensing further fortify a comprehensive plant protection strategy (Hampel et al., 2018). Crucially, integrating insights from both physical and social sciences with the perspectives of local farmers and land managers is essential to offer well-informed guidance to policymakers in bolstering resilient strategies (**Figure 3**). This requires collaborative efforts spanning the public and private sectors to navigate the complexities of disease management and climate adaptation effectively (Gupta et al., 2018).

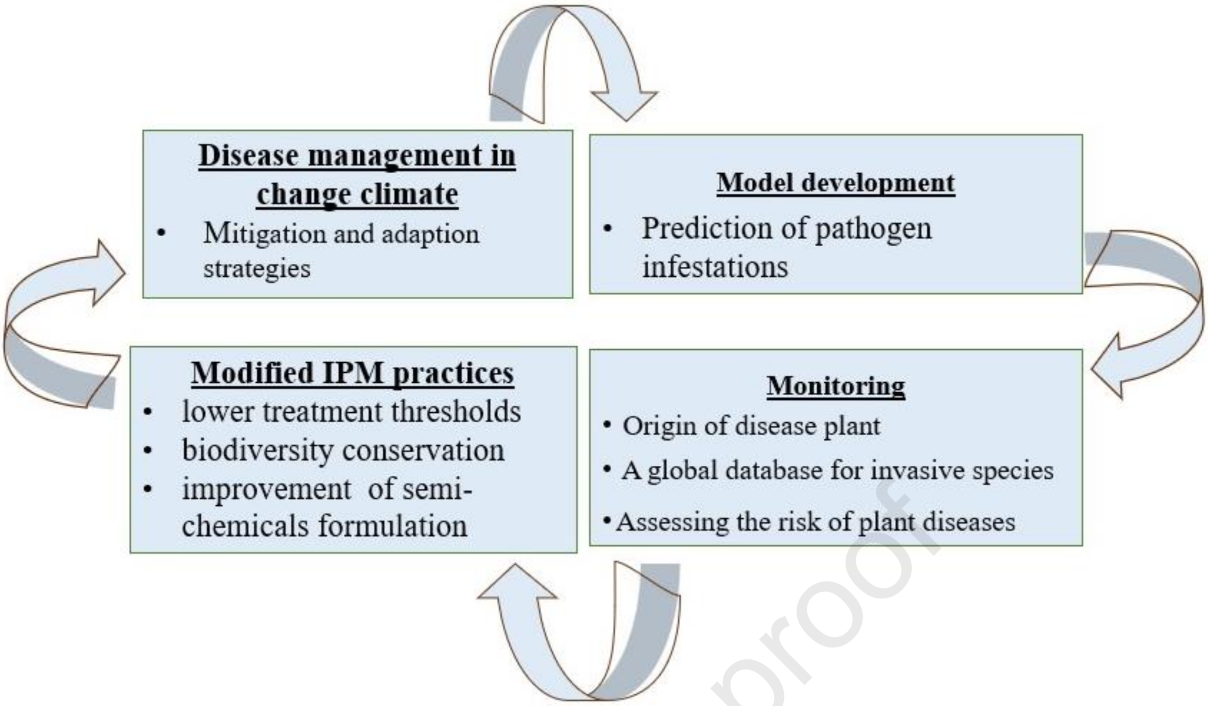

**Figure 3.** Layout of the basic formulation of plant disease management strategies as affected by changing climate.

When crafting these management strategies, it is paramount to factor in the implications of climate change while ensuring they remain economically viable and not excessively resource-intensive, as this could impede their adoption (Desai et al., 2021). Nevertheless, adaptation strategies vary depending on agricultural systems, geographical location, and projections of global climate change. At more advanced stages of adaptation, significant changes in cropping systems and crop types may be necessary. Beyond mere adjustments in field management, the possibility of relocating cultivation zones may arise in response to the emergence of new agricultural areas shaped by shifting climatic conditions. The primary avenues for climate change adaptation and mitigation generally fall into three categories: resource conservation technologies, crop system technologies, and socio-economic or policy interventions (Venkateswarlu and Shanker, 2009). Various agronomic practices offer avenues to mitigate the impacts of climate change (**Table 2**).

**Table 2.** Short and long-term adaptation strategies.

| Strategies | |
|---|---|
| **In the short term** | **In the long term** |
| ➢ Sowing date and appropriate cultivars<br>➢ Planting patterns such as high-density plantations<br>➢ Intercropping systems<br>➢ Crop residue management<br>➢ Soil health management systems<br>➢ Crop rotation<br>➢ Crop **diversification**, etc.<br>➢ Utilizing organic fertilizers could be harnessed to reduce vulnerability. | ➢ Developing stress-resistant genotypes using traditional and molecular breeding tools.<br>➢ Consistent implementation of genotyping and phenotyping will be beneficial for the development of promising genotypes. |

## 7. Future perspectives

The current landscape in plant pathology research underscores a pressing need for fundamental knowledge to leverage emerging tools effectively in disease management (Singh et al., 2023). Meeting this challenge requires a holistic approach extending beyond traditional disease monitoring and chemical controls. To enhance our capabilities, it is essential to deepen our understanding of the biological, ecological, and evolutionary responses of pathogens, vectors, and hosts to climate change. At the core of this endeavor is the identification and characterization of pathobiomes, which comprise microorganisms and invertebrates that either facilitate or impede infection and disease progression in response to climate shifts. Leveraging ecological theories, such as invasion theory and network theory, can furnish a robust framework for predicting pathogen transmission in novel environments or to new hosts, including their interactions with host and soil microbiomes (Blumenthal, 2006; Mallon et al., 2015).

Likewise, integrating evolutionary processes, such as new phenotype acquisition by pathogens or indigenous microflora through horizontal gene transfer or mutations, can deepen our understanding of pathogenicity mechanisms. Furthermore, elucidating plant phenology and disease interactions is paramount, considering that different plant species exhibit vulnerability to pathogens at distinct growth stages. For example, *Fusarium* and *Verticillium* pathogens primarily infect hosts during early growth stages, leading to wilt disease (Kirkby et al., 2013). Similarly, many diseases, like PM of grapevine and strawberry, show higher susceptibility in young leaves compared to mature leaves. Given the anticipated impact of climate change on plant growth and phenology, it is crucial to evaluate how these changes might influence plant susceptibility to disease to develop targeted disease management strategies (Jeger et al., 2021).

Measuring pathogen movement through air and water systems is vital for predicting pathogen loads resulting from climate change-induced alterations in weather patterns, wind direction, and extreme weather events. Consideration of the individual and interactive effects of climate factors such as temperature, precipitation, and drought on disease manifestation across different climatic zones is essential (Jeger et al., 2021). This necessitates establishing permanent observatories monitoring pollutants and microorganisms, complemented by drone technologies capable of sampling at elevated altitudes. Moreover, enhancing disease surveillance and management tools through remote sensing, drones, sensor-based technologies, and population genomics, coupled with advanced modeling tools, is critical for predicting future outbreaks and implementing effective risk management strategies (Burdon and Zhan, 2020; Mallon et al., 2015).

Furthermore, while much attention has been focused on diseases affecting commercial crops, the role of wild and native plants in disease incidence remains underexplored. Climate change-induced shifts in the range of wild plants may significantly impact plant disease dynamics, yet this aspect remains poorly understood (Burdon and Zhan, 2020). Similarly, the responses of plant-associated microbiomes, which play pivotal roles in disease progression or restriction, to climate change remains a knowledge gap. Additionally, socio-economic aspects must be integrated into disease monitoring and management efforts. Implementing user-friendly computational information systems supporting decision-making, especially for smallholder farmers, is crucial for effective disease management. Mobile phone-based applications can serve as useful tools due to their widespread accessibility (Burdon and Zhan, 2020).

Looking ahead, concerted efforts are needed to enhance our predictive capabilities and develop adaptive strategies tailored to the unique challenges posed by climate change-induced shifts in disease dynamics. This entails integrating cutting-edge technologies, fostering interdisciplinary collaborations, and adopting robust data-driven approaches (Burdon and Zhan, 2020). However, achieving effective monitoring and management of plant pathogens amidst climate change depends on increased research funding and policy commitments from relevant stakeholders worldwide. By prioritizing investments in research, fostering international cooperation, and embracing innovative solutions, we can strengthen global food systems and safeguard agricultural sustainability in the face of an ever-evolving climate. Research projections indicate that shifts in climatic patterns will significantly alter the dynamics of pathogen progression, host resistance, and the physiology of host-pathogen interactions, exacerbating the intensity of plant diseases. It is crucial to recognize that the impact of climate change on individual pathosystems can yield varied outcomes, ranging from positive to negative or neutral, owing to the nuanced nature of host-pathogen interactions (Jeger et al., 2021).

## 8. Conclusion

The intricate relationship between climate change and plant diseases presents a multifaceted threat to global agriculture, with far-reaching implications for food security, environmental sustainability, and socio-economic stability. Throughout this review, the complexity of this dynamic was thoroughly examined. To effectively address these challenges and enhance resilience in the face of an increasingly unpredictable climate, it is essential to foster a comprehensive understanding of these processes and develop robust adaptation strategies through international collaboration. The devastating consequences of climate change on agriculture, including its profound effects on the severity, frequency, and recurrence of pests and diseases, demand urgent attention. Despite efforts to anticipate climate variations, plant health continues to suffer, leading to fluctuations in disease prevalence, crop quality, and yield.

Globally, progress in combating the impact of climate change on plant diseases has been hindered by a lack of comprehensive understanding of epidemic processes at relevant environmental and spatial scales. Effective disease management requires detailed insights at the field scale for specific diseases. Therefore, conducting meticulous assessments and evaluations of the potential impacts of climate change at a granular level is essential to elucidate the critical mechanisms and dynamics driving plant-related diseases and associated epidemics.

## List of abbreviations

a$CO_2$: atmospheric of $CO_2$

BABA: β-aminobutyric acid

C : Carbon

C° : Celsius degree

$CO_2$: Carbon dioxide

COVID : coronavirus disease

ECO2: emitted of CO2

EPN: entomopathogenic nematodes

FHB: Fusarium head blight

IDM: integrated disease management

IPCC: Intergovernmental Panel On Climate

IR: induced resistance

N: Azote

pH : potential of hydrogen

PM : Powdery mildew

ppm : part per million

ppmv : parts per million by volume

Sheath blight (ShB)

STB: Septoria tritici blotch

UV : Ultraviolet

## Availability of data and materials

Not applicable.

## Authors' contributions

RL, TM, SL : Conceptualization, methodology. RL, TM, SL GG: writing—original draft preparation. AA, ME, RE, AM, ZB, KA, EAB : formal analysis. AA, RE, ZB, KA, R.L., EAB : Investigation. AM, ME, EAB, RL : writing—review and editing. RL: Validation. RL : supervision.

## Declarations of competing interest

The authors declare no competing interests.

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## Highlights

- Elevated $CO_2$ levels exacerbate plant-pathogen interactions, leading to more complex disease dynamics.
- Climate change directly influences crop physiology, productivity, and associated microbiota, including pathogens.
- Changes in climate alter the distribution, abundance, and virulence of pathogens, affecting crop health.
- Increasing temperatures might shift disease pressure geographically, as predicted by process-based models.
- Mitigation strategies may include breeding resistant crops and implementing integrated pest management practices.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: