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Review

Soilless Agriculture at a Crossroads: Strengths, Challenges, and Prospects of Hydroponics, Aquaponics, and Bioponics in Relation to Precision Farming

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Abstract

In the face of escalating global challenges, including climate change, food insecurity, freshwater scarcity, soil degradation, and rapid urbanization, soilless farming systems, such as hydroponics, aquaponics, and bioponics, have emerged as innovative and sustainable farming solutions. Combined with precision agriculture technologies, these systems enable real-time optimization of inputs through smart sensors, automation, and predictive modeling, significantly reducing resource consumption while improving crop yields. This review provides a unique contribution by integrating and comparing the three major soilless systems within a single framework and by highlighting, for the first time, their potential synergies with precision agriculture. It critically examines soilless cultivation systems and their relationship with precision agriculture, assessing the agronomic, environmental, and economic benefits as well as the main challenges, including high initial costs, high energy consumption, the complexity of managing biological inputs, the lack of standardized protocols, and limited accessibility for small-scale producers. The review highlights the need to integrate renewable energy sources, develop biodegradable substrates, apply life cycle assessment methodologies, and implement adequate training and regulatory frameworks to promote wider adoption and sustainability.

Keywords: hydroponics; aquaponics; bioponics; precision agriculture; sustainable production

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1. Introduction

Faced with a growing global population and significant challenges related to food security, agriculture must increase production sustainably and responsibly [1]. According to projections, the world population will reach approximately 9.7 billion in 2050, requiring a 50–70% increase in food production to meet future demand [2]. Moreover, nearly one-third of arable land is already degraded, and agriculture remains the largest consumer of global freshwater resources, accounting for approximately 70% of total withdrawals [3]. These combined pressures underscore the urgent need to develop innovative, resource-efficient, and environmentally sustainable production systems capable of ensuring long-term food security [4–6].

To address these constraints, soilless farming systems have emerged as an innovative and promising alternative to traditional agriculture, especially in areas facing water scarcity and soil degradation [7]. These systems grow plants in controlled environments, often using water-based substrates, allowing precise and optimized nutrient delivery [8]. The most common techniques include hydroponics [4], aquaponics [5], and bioponics [6]. They have demonstrated remarkable yield performances often 200–300% higher for leafy vegetables [9,10] while simultaneously reducing water consumption by 80–95% compared with open-field cultivation [11], making them well-suited for regions with limited water resources or arable land [12].

However, despite these advantages, soilless systems require large amounts of energy for pumping, filtration, climate control, and artificial lighting, which can result in high energy consumption, sometimes exceeding 250–350 kWh$\cdot$m$^{-2}\cdot$year^{-1} in vertical or greenhouse setups [13]. Energy demand further increases due to the intensive use of LED lighting and continuous water circulation [14]. The management of organic waste and/or wastewater generated by soilless growing systems represents a major environmental challenge, with the potential to affect groundwater through the infiltration of residues, nutrients, and chemical contaminants [15]. While these systems recycle water efficiently, they still require periodic nutrient solution renewal to prevent contaminant buildup, which can result in significant water use [16]. In addition, the use of non-biodegradable or non-renewable substrates, common in soilless, raises concerns about long-term sustainability [17]. Finally, the high installation costs and the reliance on advanced technologies considerably hinder large-scale adoption, particularly for smallholder farmers and in developing countries. Initial investments for commercial hydroponic systems can exceed USD 300,000, and operating costs vary substantially depending on the technological level, energy requirements, and local energy prices [18].

The integration of precision agriculture into these soilless systems has greatly improved their performance [19]. Smart sensors and automation make it possible to monitor and control key parameters such as pH, temperature, electrical conductivity, and dissolved oxygen in real time [20]. This approach optimizes resource use, reduces waste, and ensures more stable and reliable crop production [21–23]. Recent advances in artificial intelligence (AI) and machine learning (ML) have added new possibilities, enabling predictive models that anticipate plant needs, detect stress early, and automatically adjust culture conditions to maximize yield and sustainability [24,25]. The integration of these tools into hydroponic systems is already well established, with automated management software that efficiently monitors irrigation, fertigation, and climate control [26]. However, in aquaponics, the integrated management of the biological needs of fish, plants, and biofilters remains complex [27–29]. In bioponics, which relies on often variable sources of organic nutrients, real-time monitoring remains limited due to technical and operational restrictions, and modeling applications in this context are still a long way from being implemented [30,31].

Although numerous studies have examined hydroponics, aquaponics, bioponics, and precision agriculture separately, few provide a truly integrated, critical, and comparative analysis of these approaches [17,22,27,32]. In this context, this review aims, on the one hand, to evaluate the performance of soilless agricultural systems from a technical, environmental, economic, social, and health perspective; secondly, to analyze the current contributions of precision agriculture to these systems and highlight their limitations; and finally, to identify future research priorities, particularly for improving integration and synergy between soilless systems and precision agriculture tools.

2. Soilless Agricultural Systems

Soilless farming systems have emerged as a modern alternative to traditional agriculture. In these systems, natural soil is replaced by controlled nutrient solutions, ensuring a direct and optimized supply of essential minerals and allowing precise management of cultivation parameters (Figure 1) [16].

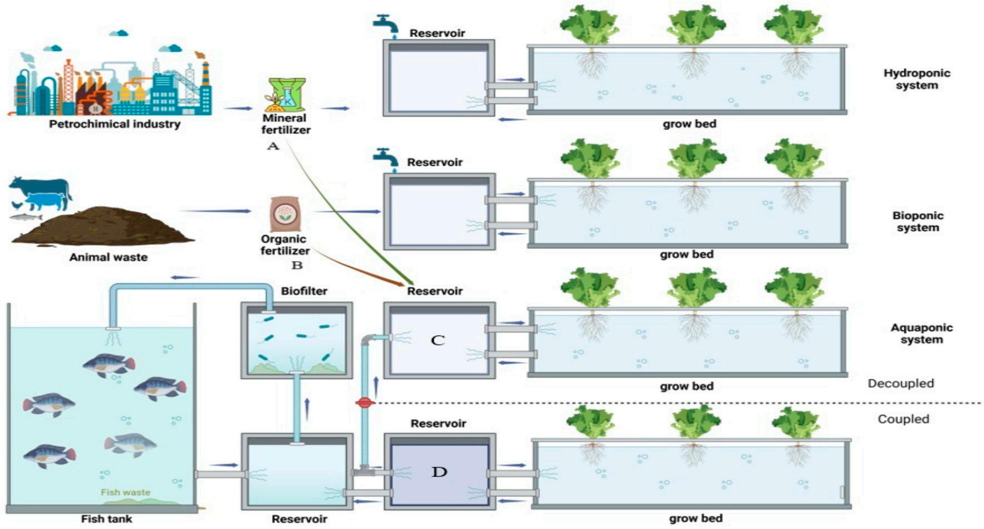

Figure 1. Overview of various soil-less cultivation systems: hydroponics (using mineral fertilizers), bioponics (using organic fertilizers), and aquaponics (including both coupled and decoupled configurations integrating fish, biofilter, and plants). **A**: Decoupled system supplemented with mineral fertilizers derived from the petrochemical industry. **B**: Decoupled system supplemented with organic fertilizers sourced from animal waste. **C**: Decoupled (non-recirculating) aquaponic system, where water flows from the fish component to the plant component without returning. **D**: Coupled (recirculating) aquaponic system, where water continuously cycles between the fish and plant components.

Today, soilless cultivation plays a central role in controlled environment agriculture (CEA), a key form of facility agriculture, and in the expansion of urban agriculture [33]. Greenhouses, growth chambers, and vertical farms enable continuous, year-round production through the control, or semi-control, of temperature, humidity, CO_2, light, and nutrient concentrations [34]. Such environmental regulation can improve yield stability, enhance product quality, and reduce the incidence of pests and diseases [35]. In urban settings, these technologies support local food production in rooftop greenhouses, building-integrated farms, or modular container units, helping shorten supply chains, lower transport-related emissions, and provide fresher produce to consumers [36,37].

Yet, despite these advantages, soilless systems implemented in controlled environments and urban areas still face several challenges [38]. These include high energy demand for environmental regulation (heating, cooling, lighting, and ventilation) [39], as well as the construction and operation of facilities that require substantial financial investments [40]. Additional constraints involve regulatory and spatial limitations in case of urban agriculture, and difficulties in the large-scale adoption of these technologies, partly due to limited public acceptance and concerns about their high technological intensity [41–43].

In addition, although many studies have examined various soilless cultivation systems and described their historical development, technical foundations, and benefits, most of them analyze each technique separately [32,44]. Integrated comparisons remain limited, and the potential links between these systems and the principles of precision agriculture are still rarely addressed.

Among the different techniques for soilless farming, hydroponics stands out as the most ancient, widely studied, and largely applied [45]. It optimizes food production in reduced areas and represents an innovative approach to several global challenges related to urbanization, water scarcity, climate change, and environmental degradation [46]. Based on the use of inert substrates and mineral nutrient solutions, it improves the efficiency of nutrient absorption and has been largely commercialized [47]. Hydroponic systems rely on strict control of EC (1.5–2.5 mS·cm^{-1}), pH (5.5–6.5), and dissolved oxygen (>5 mg·L^{-1}), as these parameters directly govern ion availability and root uptake [46]. Its main variants, such as Nutrient Film Technique (NFT), Deep water culture (DWC), and aeroponics, are described in detail in the literature but are beyond the scope of this review [48–51]. The integration of precision agriculture, through Internet of Things (IoT) sensors and artificial intelligence, now makes it possible to optimize irrigation, fertilization, and crop management, thereby enhancing its potential for sustainable and efficient agriculture.

However, despite these advantages, hydroponics has several important limitations that are holding back its widespread use [52]. The high initial cost of installations remains an impediment for small farmers [53]. International surveys have shown that initial investments can reach up to 300,000 dollars in the United States [54], and around 25,000 euros in Greece [55], while requiring 2–3 years to achieve break-even [56]. In addition, annual operating costs remain substantial, ranging from 6000 to 35,000 euros in Europe or Australia, and up to 290,000 dollars per year in large-scale systems [54]. These wide cost disparities primarily reflect variations in system size, technological sophistication, crop selection, and geographical context, including labor expenses, energy prices, and local climatic constraints. Overall, the financial burden and variability of costs underscore the considerable economic risks and uncertain return on investment associated with soilless agriculture.

In addition, these systems rely on a complex technological infrastructure, including pumps, sensors, lighting, and artificial heating, which results in significant energy consumption, while also making them vulnerable to technical failures [57]. In indoor hydroponic cannabis cultivation, energy consumption can reach 21,866,400.00 kJ per kilogram of product, with approximately 50% attributed to heating, ventilation, and air conditioning (HVAC) systems, and 33% to lighting [58]. This energy demand tends to increase with the system's complexity [59,60]. In the same way, hydroponic lettuce production in Yuma, Arizona requires an average of 90,000 $\pm$ 11,000 kJ/kg, which is about 82 times higher than conventional open-field lettuce, estimated at 1100 $\pm$ 75 kJ/kg, despite significantly higher yields [61]. For tomatoes, energy needs range from about 800 kJ/kg in open-field farming to 2140–4080 kJ/kg in greenhouses in warm regions like Almería, Spain, and can be up to 150 times higher in colder climates, highlighting how strongly local climate shapes system performance and the overall sustainability of hydroponic production [62]. This highlights the high variability as well as the trend in energy requirements, which are significantly more than in conventional agriculture, depending on both the type of crop and the climate context, posing a major challenge for environmental sustainability.

The use of coated seeds, often enriched with chemical substances such as fungicides, insecticides, or neonicotinoids, adds another layer of complexity [63,64]. These products, released gradually during germination, can cause physiological stress in plants and disrupt nutrient uptake [65,66]. In addition, neonicotinoids have a proven effect on biodiversity, particularly on wild and honeybees, even in outdoor hydroponic systems [67,68]. The substrates used also present problems since rockwool, a commonly used inert substrate, is non-biodegradable, difficult to recycle, its production is energy-intensive, and can pose health risks due to the release of irritating particles [69]. Peat moss, another substrate, is a limited resource that regenerates slowly, making its extraction environmentally harmful [70], its use contributes to the degradation of peatlands, key carbon sinks, thus worsening greenhouse gas emissions. Coconut fiber has become a popular alternative due to its biodegradability and good water retention properties [71]. However, its production requires intensive processing, including washing and buffering, which consumes large amounts of water and can cause environmental pollution if not properly managed [72]. In this context, recent research has explored other organic substrates derived from renewable resources. Among them, sphagnum moss biomass has shown promising potential, while sheep wool and hemp have proven to be less effective in hydroponic systems [73].

The search for more sustainable substrates is part of a broader effort to improve the environmental performance of hydroponic systems. In the same way, an emerging technique known as thin-layer panoponics has recently been developed. Based on the application of an ultrathin layer of Cambrian clay onto a reusable hydrophilic support, this approach operates independently of conventional substrates. Early evaluations highlight its potential in terms of productivity and operational stability, including under challenging or extreme environmental conditions [74,75].

Although hydroponics is often praised for its low water consumption, data show significant variations depending on the crop. Lettuce cultivation in hydroponics requires an average of 20 $\pm$ 3.8 L/kg/year, compared to 250 $\pm$ 25 L/kg/year for field-grown lettuce [61]. Similarly, hydroponic tomato cultivation consumes about 4 L/kg, whereas open-field production can require up to 60 L/kg [76]. These findings confirm the high water-use efficiency of hydroponics but also highlight its reliance on a constant supply of synthetic mineral nutrients from the petrochemical industry [77], which increases the system's carbon footprint due to the greenhouse gas emissions associated with fertilizer production [78]. This dependence on synthetic fertilizers, coupled with the often-limited capacity for nutrient recycling, underscores the need to optimize system management to reduce overall environmental impacts [79,80]. Yolanda et al. [81] reported a total nitrogen removal rate of only 27.5% and an ammonium removal rate of 22.6%, confirming the need for additional treatment before discharge. Poor management of these processes could result in the release of chemical residues into the environment, posing an ecological risk [82], which also adds extra costs for treatment and pollution control.

In terms of phytosanitary aspects, hydroponics is not without risks. The rapid propagation of plant pathogens through the nutrient solution has been highlighted in several studies. This rapid spread occurs because all plants share the same recirculating nutrient solution, allowing pathogens introduced at a single point to disseminate quickly throughout the entire system [83,84]. Fungal pathogens such as *Fusarium oxysporum* Schlecht. emend. Snyder & Hansen, *Fusarium solani*, *Pythium aphanidermatum*, and *Phytophthora capsici* can disseminate quickly in the absence of effective preventive measures [85]. Beyond plant health, hydroponic systems can also pose risks to human health. A study on hydroponic lettuce identified *Enterococcus faecalis* as a predominant human pathogen, posing potential dangers, particularly for immunocompromised individuals [86]. Furthermore, in closed-circuit systems such as DWC, water stagnation can promote the growth of algae such as *Chlamydomonas* and *Scenedesmus* [87]. It may also foster opportunistic human pathogens, notably *Citrobacter freundii*, *Escherichia coli*, *Klebsiella oxytoca*, and *Listeria monocytogenes* if the system is not properly disinfected between production cycles [88].

The development of hydroponics for other crops, such as cereals, tubers, and fruit trees, remains limited. These cultures present complicated morphophysiological structures that make their adaptation difficult [89–91]. Lastly, the organoleptic and nutritional aspects of hydroponic products are often different from those grown in soil, with implications for taste, texture, or aroma [92]. These changes make acceptance harder, since consumers are used to the classic flavor of soil-grown crops. For example, hydroponic tomatoes develop specific volatile compounds such as 2-methylpropanol, 2,3-pentanedione, and (*Z*)-3-hexen-

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1-ol, giving them fruity and grassy notes that differ from the traditional taste [93]. Similarly, hydroponic lettuce shows higher acidity, lighter color, and a crisper texture, creating a sensory profile that can also reduce acceptance among consumers familiar with soil-grown lettuce [94].

As an extension of hydroponics, and in response to some of these environmental and resource-use limitations, aquaponics represents an integrated evolution that combines soil-less plant production with fish farming, offering a circular and potentially more sustainable approach to food systems [95]. Its operation relies on nitrifying bacteria, mainly *Nitrosomonas* and *Nitrobacter*, which convert fish metabolic waste into mineral nutrients readily available for plants [96]. The efficiency of this nitrification process is highly sensitive to temperature (optimal 25–30 °C) and pH (7.2–8.2), which regulate the activity of Nitrosomonas and Nitrobacter and directly affect the rate at which ammonium is converted into nitrite and nitrate [96,97]. Through continuous water recycling, aquaponics significantly reduces water losses and requires limited freshwater input, although its environmental benefits largely depend on system design and performance [98,99]. Aquaponic systems can reduce overall water use by 80–95% compared to conventional agriculture, while achieving biological conversion rates of 90–99% for ammonium through nitrification, ensuring efficient nutrient recycling [100]. Over time, aquaponics has evolved from small-scale coupled configurations to advanced decoupled systems, opening new perspectives for the commercialization of both plants and fish [9]. Combined with precision agriculture technologies, these systems allow for more efficient and specialized resource management, better tailored to the specific needs of crops and fish [101,102]. Although still emerging, aquaponics is increasingly recognized as a strategic tool for sustainable food production, providing protein- and mineral-rich foods to meet the growing demand of the global population [103]. Compared to conventional agriculture, aquaponic systems show potential economic advantages due to enhanced production efficiency and the ability to generate high-value products [104]. They support the cultivation of a wide diversity of fish species (herbivores, omnivores, and carnivores) such as trout, tilapia, bass, grass carp, and catfish [105–107], while simultaneously enabling the production of various plants including lettuce, basil, and tomatoes [108–110]. However, aquaponics not only shares the same challenges as hydroponics in terms of plant production, such as high energy demand, technological complexity, and costly infrastructure, but also introduces additional layers of complexity related to biofilter management and fish farming [108]. This complexity arises from the fact that fish, plants, and nitrifying bacteria each require different optimal ranges for temperature, pH, and dissolved oxygen, making it inherently difficult to maintain conditions that simultaneously satisfy all three biological components [96,107–109]. This extension of the system involves even heavier investment, as setting up an aquaponics system requires fish tanks, water recirculation systems, and advanced hydroponics facilities. These investments can range from 130,000 $ to 1,300,000 $, making access to this technology particularly difficult for farmers in low-resource regions [111]. In addition, the energy consumption associated with aquaponic systems, especially for water recirculation, aeration, and heating, constitutes a significant fixed cost [112]. Although integrating renewable energy sources can reduce dependence on fossil fuels, it requires additional investment [113].

In aquaponics, coupled systems where water continuously circulates between the aquaculture and hydroponic units present specific operational constraints [114]. In such systems, the use of conventional chemical pesticides and antibiotics is prohibited to safeguard fish health and ensure overall system stability [115]. Although this restriction is advantageous for producing cleaner and more environmentally friendly food, it necessitates the adoption of alternative pest and disease management strategies, such as biopesticides or biological control methods [116]. Implementing these alternatives may, however, result in additional costs and technical challenges for farmers [117]. Moreover, operating a coupled aquaponic system requires multidisciplinary expertise encompassing fish physiology, plant nutrition, and water management, this complexity may act as a barrier for adoption, especially among non-specialists [98]. However, recent advances in predictive modelling, automation and real-time monitoring technologies offer promising solutions to ease system management and reduce the technical expertise required [118,119]. The technical management of aquaponic systems represents an additional major challenge, requiring regular maintenance of water recirculation and aeration systems, as well as precise monitoring of nutrient levels, which requires specific skill [98]. Without proper management, the risk of system failure is high, which can lead to significant fish and crop losses [95]. The need to maintain a precise balance between fish waste production and plant nutrient uptake adds a layer of complexity, excessive waste and organic matter can damage plant roots if not properly treated, and may lead to plant toxicities [120,121].

Moreover, the aquaponic system relies on a delicate balance, incorporating a third biological element: the biofilter [122]. This balance can be difficult to maintain due to the differing ecological needs of the species involved [122]. Some cold-water fish require cool, well-oxygenated water to grow optimally [97]. However, these conditions are often not compatible with the temperatures required for effective nitrification, whose action is crucial for nutrient recycling in the system, which also affects the availability of nutrients for plants [123]. Farming fish in confined environments, particularly in closed-circuit systems or high-density ponds, presents significant health risks [124]. Once fish are introduced into confined aquaculture environments the resulting crowding and spatial restriction create conditions conducive to the development and spread of infectious diseases such as columnaris [125], dropsy [126], and fin rot [127], which are further exacerbated by stress and suboptimal environmental parameters commonly encountered in intensive systems, ultimately compromising not only individual fish health but also the stability of the entire aquatic ecosystem by disrupting its biological equilibrium and jeopardizing the long-term viability of production [128,129]. Furthermore, the presence of silent pathogens, such as *Saprolegnia* in fish can progressively impair system performance without immediate visible signs, making preventive management of these health risks difficult [128,130–132].

Furthermore, some high-value species, notably migratory fish, are poorly adapted to captivity due to the complexity of their life cycles, which increases their vulnerability to diseases [133,134]. In addition, aquaponics, like other fish farming systems, depends on natural resources to feed the animals, which creates ethical and environmental concerns, the feed and fish oil often come from wild species caught by large fishing industries, this puts pressure on marine ecosystems and makes aquaponics dependent on industrial fishing [135,136]. This dependence is at the center of current discussions, particularly about the need to find sustainable alternatives for feeding farmed fish. Exploring alternative protein sources, such as plant-based proteins or insects, is therefore essential to reduce the overall environmental impact of these systems by decreasing reliance on fishmeal from industrial fishing, which contributes to the overexploitation of marine resources [137,138]. Indeed, this type of basic feeding impacts the nutritional quality of farmed fish, whose protein content and essential fatty acid levels are often lower than those found in wild fish [139,140].

On the other hand, although the use of various water sources such as rainwater or borehole water is aligned with sustainable practices, it can lead to the introduction of chemical contaminants and microbial agents [141,142]. Without proper monitoring and control, these contaminants may negatively affect the health of fish and plants, ultimately compromising consumer health [143,144].

Regulatory constraints represent a further obstacle to the expansion of aquaponics, mainly due to unclear legal frameworks or overly strict legislation regarding product certification [145]. In many countries, aquaponic products face difficulties in obtaining appropriate food certifications, limiting their market access [98]. In the EU, for example, aquaponics cannot be certified as organic because vegetables must be soil-grown and fish raised in Recirculating Aquaculture Systems (RAS) do not meet animal welfare standards [146]. In Portugal, additional barriers include the prohibition of key species such as tilapia, duplicated licensing procedures between aquaculture and agriculture, and the absence of an official certification scheme [145]. These limitations reduce competitiveness, discourage investment, and highlight the need for alternative labels such as organic aquaponics.

In addition to aquaponics, and in line with the search for more sustainable nutrient sources, another development in the plant sector is bioponics, which uses organic matter (food waste, manure, animal slurry) as a source of nutrients for plants, rather than directly integrating livestock into the production process [6]. In bioponic systems, nutrient availability depends on the microbial mineralization of organic matter, a process in which bacteria and fungi progressively convert complex molecules into plant-available ions, resulting in slower and less predictable nutrient release compared to mineral hydroponic solutions [147,148]. Furthermore, bioponics aligns with sustainability goals and the valorization of organic waste [149]. In some aquaponic farms, fish excrement is collected, decanted, and used to fertilize plants such as lettuce or tomatoes [150]. Similarly, poultry farms have begun converting chicken manure into liquid extracts for use in soilless cultivation [31]. Aquaponic and bioponic systems reduce dependence on costly and resource-intensive mineral fertilizers compared to hydroponics, enhancing sustainability through the exclusive use of organic nutrient sources [151]. Several studies have reported comparable or even superior biomass production results compared to traditional agriculture and hydroponics, highlighting its potential as an alternative production system [152]. However, other studies have reported lower yields under certain conditions, highlighting the need for further optimization and standardization [6]. However, despite its environmental potential, bioponics faces several significant limitations that hinder its large-scale adoption [45]. One major challenge lies in the large quantity of organic sludge required to meet the nutritional needs of plants [153]. This requirement makes the method difficult to apply in certain agricultural contexts, especially in urban or peri-urban areas where access to such sludge is limited or strictly regulated [6].

Before any form of reuse, sludge must undergo thorough treatment, primarily to decompose organic matter and promote mineralization, thereby minimizing health and environmental risks [154]. This typically involves steps such as sedimentation, filtration, and crucially, aerobic or anaerobic digestion, which are essential for transforming organic pollutants into more stable and safer forms [155]. Without such treatment, sludge may contain high levels of Zinc, Copper, and other heavy metals [156], antibiotics [157], or pathogenic microorganisms such as *Salmonella* or *Escherichia coli* [158,159], which have the potential to disrupt the balance of the system and ultimately pose serious health risks. Moreover, aerobic digestion can generate toxic gases like ammonia and hydrogen sulfide, both of which are known to have carcinogenic effects [160]. As a result, strict biosafety measures are required to safeguard both workers and the surrounding environment [161].

Another critical issue concerns the nutritional composition of organic fertilizers, these do not always fully meet the mineral requirements of plants [162]. For example, fish-derived solid sludge is high in nitrogen but low in potassium and magnesium, two essential elements for flowering and fruit development [163]. This forces growers to supplement mineral additives, thereby limiting the appeal of a fully bioponic system and raising questions about its long-term sustainability [164]. In addition, plant growth is often slower in bioponic systems than in traditional hydroponics [149]. These fluctuations occur because nutrient availability depends on the biological mineralization of organic matter, a slow and temperature-dependent process in which microorganisms must first break down organic matter to release bioavailable nutrients, a process that can take several days [156], causing nutrients to be released gradually rather than remaining immediately available as in mineral hydroponics [165]. On the technical side, residual particles from the sludge, even after filtration, can accumulate in pipes and cause clogging [166–168]. This phenomenon will be particularly comm on in NFT systems or vertical farming setups [100].

While encouraging results have been observed in pilot-scale systems, large-scale data is still lacking to assess performance across diverse agricultural settings [6,148]. Furthermore, implementing bioponic systems requires specialized infrastructure and technical expertise, leading to significant costs, particularly in developing countries [169]. The lack of adequate organic waste management systems and appropriate technological solutions further limits widespread adoption of bioponics, as the infrastructure needed to support these systems is often lacking [170]. The main characteristics, advantages, and limitations of hydroponics, aquaponics, and bioponics are summarized in Table 1 for comparison.

Table 1. Comparative overview of soilless cultivation systems.

System	Principles	Advantages	Limitations/Challenges	References
Hydroponics	Plants cultivated on inert substrates with mineral nutrient solution.	High water-use efficiency; High yields; Precise control of cultivation parameters; Compatible with IoT & AI technologies.	High initial investment; High energy; Dependence on synthetic fertilizers; Unsustainable substrates; Pathogen spread through nutrient solution; Organoleptic differences compared to soil-grown crops.	[53–55,58,61–63,66,70,72,86]
Aquaponics	Integration of aquaculture and hydroponics through nitrifying bacteria.	Reduced water consumption; Dual production of fish and plants; Valorization of organic waste; Potential for high-value products; Circular food production model.	High capital investment; Significant energy demand; Complex management; Fish diseases; Dependence on fishmeal and fish oil; Regulatory barriers.	[95,98,111–113,125–127,146]
Bioponics	Use of organic matter as nutrient source.	Valorization of organic waste; Reduced dependence on mineral fertilizers; Sometimes comparable yields to hydroponics; Aligned with sustainability goals.	Requires large quantities of sludge; Mandatory treatment; Chemical risks and microbial risks; Nutrient imbalance; Slower growth; Pipe clogging from sludge particles; Infrastructure costs and technical expertise.	[6,153,156,157,161,164,165,168–171]

3. Precision Agriculture Strategies and Their Integration with Soilless Cultivation Systems

Precision farming, also called smart farming, is a modern approach to agriculture that uses advanced technologies such as electronics, robotics, sensors, automation systems, and the Internet of Things (IoT) (Figure 2) [172]. Most precision-agriculture systems operate through closed-loop control, where sensors continuously measure key variables (EC, pH, temperature, dissolved oxygen) and transmit data to controllers that activate actuators such as nutrient dosing pumps, irrigation valves, ventilation units, or CO_2 injectors to maintain optimal growing conditions in real time [118,173]. These tools work together to collect, process, and analyze different types of data, including time-based, location-specific, and plant-specific information [174]. The collected data is then combined with other sources such as weather forecasts, crop growth models, and past performance records to support decision-making based on observed variability and specific crop needs [175,176]. This approach aims to increase productivity and reduce input waste, which is particularly relevant for soilless systems [177].

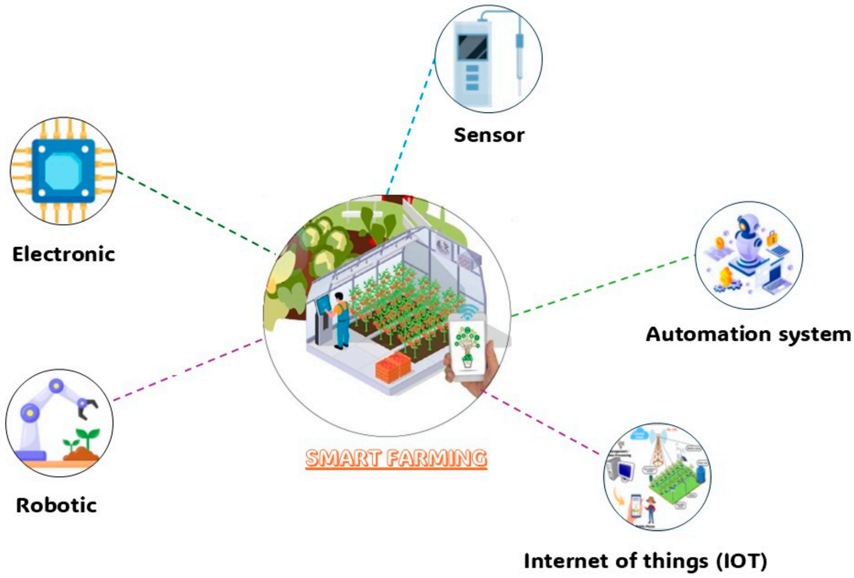

Figure 2. Smart farming: integration of electronics, robotics, sensors, automation systems, and IoT to optimize crop management in soilless agriculture.

Soilless systems are highly sensitive to environmental and nutrient imbalances [38,178]. Precision farming offers a promising way to optimize their management by allowing fine control of growing conditions [21]. It enables real-time monitoring [179] and dynamic adjustment of key factors such as nutrient supply [180], light intensity [181], temperature, irrigation, and CO_2 concentration [182]. Many studies highlight its potential to improve resilience and resource efficiency [19,20,183]. In controlled-environment agriculture, sensor-based automation has been shown to reduce water and fertilizer use by 20–50% while increasing crop yields by 10–30%, demonstrating its strong potential for resource-efficient management [184]. One of the most significant aspects concerns the monitoring of water quality, which previously relied on laboratory tests but can now be performed using smart sensors that provide continuous, real-time tracking of temperature, pH, electrical conductivity (EC), and relative humidity [185,186]. EC sensors can automatically control nutrient dosing through peristaltic pumps [187], and root-zone humidity sensors can adjust irrigation based on plant water needs [51]. In greenhouses, temperature and CO_2 sensors can control ventilation to keep the climate optimal [188,189], while power cuts can trigger mobile alerts to prevent crop loss [190].

Beyond these advantages, precision agriculture is still at an early stage and requires further research to assess its long-term effects on crop performance, as well as its environmental and socio-economic impacts [191,192]. Firstly, producing automated equipment often uses non-sustainable materials like rare metals, plastics, and electronics, whose extraction has a high carbon footprint. Beyond the environmental impact of their production, the issue of machine reliability also arises, as these devices gradually lose accuracy and require recalibration or replacement, which generates costs and waste when recycling is not properly managed [193]. This limitation is most evident in pH, EC, temperature, and CO_2 sensors, which are key to tracking growing conditions and nutrient availability. Sensor failures can cause yield losses of up to 30% [194], while incorrect CO_2 or bicarbonate readings can acidify the nutrient solution and harm plant uptake [195].

In addition to these risks related to sensor reliability, the accurate measurement of nutrients remains a major challenge. Nitrate (NO_3^-), ammonium (NH_4^+), and phosphate (PO_4^{3-}) are particularly difficult to quantify in organic or complex nutrient solutions [196], and their monitoring often requires frequent recalibrations or laboratory analyses to ensure data reliability [197]. Moreover, the limited availability of affordable and reliable equipment for nutrient analysis, combined with the high costs of acquisition, calibration, and maintenance, significantly reduces the accessibility of these technologies for small-scale producers [198].

In addition to these technical issues, energy use is another major concern, as automation can increase energy consumption by 10 to 30% compared to traditional greenhouses [199,200]. According to a Wageningen UR study, high-tech greenhouses can require 4 to 8 times more energy than low-tech structures, due to advanced climate control and CO_2 systems [120]. For example, producing tomatoes may require about 191 kcal/kg in a conventional greenhouse, but 2300 to 4375 kcal/kg in an automated one [201]. While automation can improve yield stability, power outages remain a serious risk, as they can shut down essential systems such as pumps [202].

The effective use of these technologies also requires specialized technical skills as well as strong expertise in agronomy and environmental sciences [203,204]. Finally from a socio-economic perspective, the rise in automation could reduce agricultural employment opportunities, particularly in rural areas where agriculture remains a key source of income [205,206]. In the long term, it could further contribute to the erosion of traditional agricultural knowledge and practices [207].

While automation and smart sensors enhance real-time monitoring and control, their limitations in terms of reliability, cost, and accessibility highlight the need for complementary approaches [173]. In this regard, modeling emerges as a fundamental pillar of precision agriculture in soilless systems, providing predictive insights and optimization strategies that go beyond immediate sensor feedback [208–212]. These technologies can simulate complex scenarios involving nutrients, pH, temperature, and CO_2, helping farmers anticipate problems before they affect crops [213], optimize water, fertilizer, and energy use by linking predictive algorithms to real-time sensor data [214]. This dynamic is particularly well developed in hydroponics, where simulation tools now allow producers to more finely adjust nutrient supply and climatic conditions, which often improves yields [32]. These technologies reduce the need for physical trials, lower input waste, and improve the reliability of yield predictions, offering both economic and environmental benefits [215]. These advances rely on a variety of modeling approaches, ranging from mechanistic models which simulate nutrient uptake, water movement, and root-zone dynamics using plant physiology and mass balance equations [208,216], to data-driven models such as Random Forest and Extreme Gradient Boosting (XGBoost), which predict biomass, growth stages, and nutrient requirements based on various data such as pH, EC, temperature, humidity, light intensity, and sometimes CO_2 [217]. The value of these approaches is illustrated by practical applications: for instance, Sharmin et al. [217] applied Random Forest to estimate nitrogen uptake in lettuce under different conditions, achieving an R^2 above 0.9, while [218] demonstrated that XGBoost predicted tomato biomass more accurately than linear regression. These models are further supported by sensor networks that measure EC, pH, temperature, and dissolved oxygen in real time, enabling dynamic decision-making in closed-loop systems [187].

While modeling in hydroponics has already made considerable progress, its extension to aquaponics remains more complex, as it also involves fish farming and microbial processes [219]. Modeling must therefore simultaneously integrate the interactions between fish, plants, and microbial communities, each of these compartments having specific environmental requirements [220]. Current models generally focus either on fish growth, determined by variables such as temperature, dissolved oxygen, and feeding rate [221], or on the efficiency of microbial nitrification [198]. However, to date, there is no standardized and generalizable model that can integrate these dimensions in a precise and transferable manner [219]. Few studies have thus managed to relate these aspects to plant growth models, despite the obvious interdependence of all components of a functional aquaponic system [222].

To address this complexity, digital twin technologies, as demonstrated by Ghandar et al. [103], make it possible to simulate the entire system in order to balance fish waste production, water quality and plant nutrition. Similarly, some modeling approaches to the challenges of the wastewater treatment sector such as activated sludge and biofilm models offer a promising framework for representing microbial and nutritional dynamics in aquaponics, although they are still rarely applied in this context [223].

Compared to hydroponics and aquaponics, bioponics remain the least explored soilless cultivation system in terms of modeling [149]. Its specificity lies in the use of organic nutrient solutions, where nutrient availability depends on complex biological mineralization processes rather than on directly soluble mineral salts, This added biological dimension makes the system inherently more variable and difficult to predict [147]. To date, no models exist to simulate nutrient dynamics in bioponic systems [211]. Existing monitoring tools, such as sensors for chemical oxygen demand (COD), dissolved oxygen (DO), and EC, can provide partial insights into organic nutrient availability [224], but they often face major limitations, including fouling, chemical interferences, and calibration issues, especially in complex organic matrices [197]. As a result, the development of reliable, transferable models for bioponics remains far behind other soilless systems [6]. Addressing this gap is essential for improving nutrient predictability in organic solutions and supporting the development of bioponics as a sustainable alternative to mineral-based soilless cultivation.

Alongside modeling approaches in hydroponics, aquaponics, and bioponics, Artificial Intelligence (AI), particularly machine learning (ML) and deep learning (DL), have emerged as a major tool in precision agriculture, enabling new forms of data-driven decision-making. These methods can detect complex patterns in large datasets from sensors [217] and capture nonlinear relationships between variables [218]. However, their "black box" nature often limits interpretability, making it harder to integrate them into agronomic decision-making [225]. In precision agriculture, where biological understanding is essential, this lack of transparency is a major challenge [226]. This is where SHAP values (SHapley Additive Explanations) offer a practical solution. Based on cooperative game theory, SHAP assigns each input variable an explicit, quantified contribution to each individual prediction [227,228]. This enhances the transparency of complex models and provides agronomists with actionable insights into the influence of key variables such as pH, EC, temperature, and light intensity. For instance, a recent study applied SHAP and Local Interpretable Model-agnostic Explanations (LIME) explainable AI methods to a voting regressor model predicting Thai basil growth in deep-water culture systems. The analysis revealed how different environmental variables such as light, humidity and, pH contributed to model predictions, offering interpretable insights into the factors influencing plant development under controlled hydroponic conditions [229]. Similarly, Kim et al. [230] used SHAP in a recent study on hydroponically grown soybeans to interpret how individual nutrients, such as nitrogen, magnesium, and potassium, contributed to water uptake predictions across different growth media, enhancing the transparency of machine learning models in nutrient optimization. Integrating SHAP values into modeling workflows not only makes predictions more interpretable, but it also deepens understanding of complex agro-environmental dynamics. This leads to more informed decisions, making SHAP a key tool for advancing digital agriculture that is accurate, explainable, and truly user centered.

An overview of the main strategies, benefits, and challenges of precision agriculture applied to soilless systems is presented in Table 2.

Table 2. Precision agriculture strategies applied to soilless cultivation systems.

Aspect	Applications/Principles	Advantages	Limitations/Challenges	References
Monitoring & Control	Use of IoT, robotics, sensors, EC/pH probes, CO_2 sensors, irrigation controllers.	Real-time monitoring of pH, EC, humidity, CO_2, temperature; Dynamic control of nutrient dosing, irrigation, and climate; Preventive alerts.	Sensor drift and loss of accuracy; Failures may cause up to 30% yield loss; Frequent recalibration required; High acquisition/maintenance costs.	[172,174,185–187,190]
Sustainability & Technical Limitations	Automation relies on electronics, rare metals, plastics; advanced climate control.	Increased stability of crop production; Potential yield gains under controlled environments.	Unsustainable materials with high carbon footprint; Waste/recycling challenges; Energy use increased by 10 to 30% compared with traditional greenhouses; Need for technical expertise; Risk of reduced rural employment.	[193,194,199,201,203,205]
Modeling Approaches	Mechanistic models (mass balance, nutrient uptake, water dynamics); Data-driven models (RF, XGBoost, predictive algorithms).	Predictive insights beyond sensor data; Reduced need for physical trials; Improved yield predictions; Optimized water, fertilizer, and energy use.	Complexity higher in aquaponics (fish + plants + microbes); Lack of standardized transferable models; Nutrient sensors for NO_3^-, NH_4^+, PO_4^{3-} still unreliable.	[98,103,208,217–219]
AI & Explainable AI	ML/DL for biomass, nutrient, and growth prediction; Explainability via SHAP values and LIME.	Detects nonlinear relationships; SHAP improves interpretability of complex models; Actionable insights for agronomists.	"Black box" nature of ML/DL limits trust in predictions; Need to integrate agronomic knowledge with AI outputs.	[217,218,225–230]

4. Conclusions

Soilless cultivation, when integrated with precision agriculture, offers a promising pathway toward more sustainable and resource-efficient farming models. These systems are increasingly used within controlled environment agriculture, whether in urban, peri-urban, or rural areas. They help address land scarcity, improve water-use efficiency, and stabilize year-round production. However, several limitations still hinder their large-scale adoption. Key priorities include the development of biodegradable and efficient substrates, the improvement of organic nutrient formulations, and the use of more sustainable inputs. The integration of renewable energy sources is also essential to reduce the carbon footprint and enhance the energy autonomy of controlled environment facilities. Socio-economic barriers remain significant, as high investment and operational costs limit accessibility, especially for smallholders. Wider adoption will require supportive public policies, targeted training programs, and clearer regulatory frameworks.

On the other hand, automation and modeling can enhance system precision and optimize resource use, but their effectiveness depends on reliable data and standardized, transferable tools. Future research should focus on improving energy-efficient automation, developing standardized modeling approaches, and assessing system performance under urban and extreme climate conditions. Harmonized protocols for monitoring, data collection, and environmental assessment are also needed.

Overall, a systemic and interdisciplinary approach is essential to establish soilless cultivation and CEA as credible, scalable, and sustainable alternatives to conventional agriculture capable of addressing the ecological and socio-economic challenges of the 21st century.

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