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Review

New Generation Sustainable Technologies for Soilless Vegetable Production

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Abstract: This review article conducts an in-depth analysis of the role of next-generation technologies in soilless vegetable production, highlighting their groundbreaking potential to revolutionize yield, efficiency, and sustainability. These technologies, such as AI-driven monitoring systems and precision farming methods, offer unparalleled accuracy in monitoring critical variables like nutrient concentrations and pH levels. However, the paper also addresses the multifaceted challenges that hinder the widespread adoption of these technologies. The high initial investment costs pose a significant barrier, particularly for small and medium-scale farmers, thereby risking the creation of a technological divide in the industry. Additionally, the technical complexity of these systems demands specialized expertise, potentially exacerbating knowledge gaps among farmers. Ethical considerations are scrutinized, including data privacy concerns and potential job displacement due to automation. Regulatory challenges, such as international trade regulations and policy frameworks, are discussed as they may need revision to accommodate these new technologies. The paper concludes by emphasizing that while these sustainable technologies offer transformative benefits, their potential for broad adoption is constrained by a complex interplay of financial, technical, ethical, regulatory, and social factors. Comprehensive, multi-faceted solutions are therefore essential for their ethical and equitable implementation.

Keywords: Horticulture; hydroponics; digital agriculture; sustainability; sustainable production

1. Introduction

1.1. Background on Soilless Vegetable Production

Soilless vegetable production, encompassing hydroponic and substrate-based systems, has emerged as a viable alternative to traditional soil-based agriculture [1,2] particularly in regions with poor soil quality or limited arable land. This method offers higher yields, efficient nutrient utilization, extension of harvest periods, and reduced susceptibility to soil-borne diseases [3–5]. In addition, the pressure of climate change over agricultural production is steadily increasing because of the reduction of freshwater availability [6,7], forcing producers to incorporate efficient production units such as hydroponic systems, which can aid in a context of limited water for agriculture [8]. However, a critical analysis reveals several challenges and considerations that underpin this growing field. First, if organic materials in soilless systems are not appropriately supplied to the crop, it can produce less robust microbial ecosystems, potentially affecting plant health and nutrient absorption [4]. Also, these systems often require a higher initial investment in infrastructure and technology, which can be a barrier for small-scale farmers or those in developing regions [9]. In addition, the environmental impact of soilless systems is still controversial; while they often use water more efficiently, the energy requirements for climate control and nutrient delivery can be significant [9,10]. Finally, there's a learning curve associated with managing these systems, requiring new skill sets that traditional farmers may not possess [11,12], while soilless vegetable production presents exciting opportunities for addressing some of the challenges of modern agriculture, it also introduces a new set of complexities and considerations that must be critically examined.

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1.2. Importance of Next-Generation Technologies in Advancing the Field

The importance of next-generation technologies in advancing the field of soilless vegetable production cannot be overstated. These technologies, ranging from AI-driven analytics to precision farming and advanced sensing systems, can revolutionize the industry by increasing yields, reducing resource consumption, and enhancing overall sustainability [13,14]. Nevertheless, as stated before, incorporating new types of technologies comes with several challenges to overcoming the constant increase in food demand because of population growth [15–17], potentially exacerbating existing inequalities within the sector. In addition, ethical and regulatory concerns, such as data privacy and environmental impact, remain unresolved [18–20], raising ethical questions about their widespread adoption. Additionally, the rush to adopt new technologies may lead to inadequately tested implementations, risking failing to deliver promised benefits and introducing unforeseen risks, therefore, while next-generation technologies hold promises for soilless vegetable production, their adoption needs careful deliberation and balanced judgment to address these complex challenges.

1.3. Objective of the Review Article

This review article aims to comprehensively analyze the state-of-the-art technologies and methodologies in soilless vegetable production, focusing on next-generation innovations. This includes an in-depth examination of automation and precision farming techniques, sensing and tracking technologies, and the integration of artificial intelligence and data analysis applied in soilless horticultural crops, i.e., in aquatic systems and inert substrates (hydroponics), and also the cultivation with natural organic substrates [21]. The review also aims to identify these technologies advantages, limitations, and challenges. It offers a balanced perspective that considers their potential to improve yield and sustainability and the financial, technical, and ethical considerations that may impact their widespread adoption. Furthermore, the article seeks to highlight gaps in current research and suggest directions for future studies, thereby serving as both a resource for practitioners in the field and a roadmap for researchers. In summary, the objective is to present a nuanced view that acknowledges the transformative potential of next-generation technologies in soilless vegetable production while critically examining the complexities and challenges of their implementation.

2. Hydroponic Systems

2.1. Overview of Hydroponic Systems

Hydroponic systems are a method of growing plants without soil, extracting the necessary nutrients for their growth from a nutrient solution [22]. These systems have emerged as a cornerstone technology in soilless vegetable production, offering a range of benefits from resource efficiency [17,23] to optimized plant growth [24]. One of the critical advantages of hydroponic systems is the ability to precisely control nutrient levels, electrical conductivity (EC), pH, and oxygenation [25], optimizing plant growth and resources, being more water-efficient than traditional soil-based cultivation, making them an attractive option for sustainable agriculture. This system can be categorized into several types, including Nutrient Film Technique (NFT), Deep Water Culture (DWC), and Aeroponics, each with unique advantages and applications. NFT, for instance, employs a thin film of nutrient solution that flows over the roots, powered by a water pump, providing a constant supply of nutrients and oxygen [26,27]. This system is particularly effective for leafy greens and herbs, which require less support and can thrive in these conditions.

On the other hand, DWC submerges the plant roots in a nutrient solution, using air stones to oxygenate the water [28]. This system is well-suited for plants that require more support and a stable environment, such as tomatoes and cucumbers. Aeroponics represents the most technologically advanced form of hydroponics, where nutrient solution is misted directly onto the roots, maximizing oxygen exposure [24]. This system has shown promise in rapid plant growth and resource efficiency but requires more precise control and monitoring [24,29]. The main characteristics, advantages, and disadvantages of these systems are detailed in [30,27].

2.2. Recent Technological Advancements in Hydroponics

Recent technological advancements in hydroponics have significantly transformed the field, making it more efficient, sustainable, and user-friendly. For instance, integrating Internet of Things (IoT) devices allows real-time monitoring and control of key environmental variables, such as temperature and nutrient levels, facilitating data-driven decision-making [31,32]. In addition to this, introducing specialized LED grow lights has optimized plant growth through targeted light spectrums and reduced energy consumption [33]. Artificial Intelligence and machine learning algorithms are now being employed to analyze data and predict plant growth patterns and potential diseases, enabling preemptive and more effective interventions [34]. Additionally, robotics has been introduced to automate tasks from planting to harvesting, reducing labor costs and human error [35]. Also, advanced water recycling systems have further increased the water efficiency of hydroponic setups [36,37]. Moreover, new software platforms enable remote monitoring and control [38,39], ideal for large-scale operations and multi-site growers, setting the stage for a more efficient and sustainable future in soilless vegetable production. The main advanced technologies currently applied in hydroponics, along with their advantages and disadvantages are listed in Table 1.

Table 1. Summary of recent technological advancements in hydroponics, highlighting their main advantages and disadvantages.

Advanced Hydroponic Technology	Main Advantages	Main Disadvantages
AI-Based Monitoring Systems	High precision in nutrient and pH detection, yield optimization	High cost, technical skills required for operation
Precision Agriculture Techniques	Efficient resource use, improved crop quality	High initial investment, complexity in implementation
Advanced Moisture and Nutrient Sensors	Real-time monitoring, improved irrigation efficiency	Installation and maintenance cost, potential technical failures
Automated Climate Control Systems	Precise environmental control, improved crop quality and yield	High energy consumption, operational costs
Full-Spectrum LED Lighting	Energy efficiency, improved plant growth	High initial cost, potential for plant stress if not managed correctly
Mobile Apps for Crop Management	Remote access for monitoring and control, ease of use	Connectivity dependency, feature limitations depending on the app

2.3. Impact of Hydroponic Systems on Soilless Vegetable Production

The impact of hydroponic systems on soilless vegetable production is transformative, offering a host of benefits but presenting specific challenges that merit critical scrutiny. On the positive side, hydroponic systems are highly resource-efficient, using less water than traditional soil-based farming, which makes them ideal for regions facing water scarcity [40]. They also allow for a controlled environment where variables like nutrient levels and pH can be precisely managed, leading to optimized plant growth and potentially higher yields [41]. Additionally, these systems are particularly beneficial in urban settings where space is limited, thanks to their efficient use of space [42], especially when combined with vertical farming techniques [43]. Also, the reduced need for pesticides in these controlled environments contributes to healthier produce [44].

2.4. Scalability and Replicability of Soilless Cultures

In the current context of global warming, along with the increase in urbanization and the reduction in arable land, soilless culture systems need to be expanded or scaled up to meet the increasing demand or production needs, and to maintain consistent plant growth and yield while increasing the number of plants or the size of the growing area [45]. There are several cases that have reported successful incorporation of technological advances to optimize plant production under soilless culture systems. However, a critical analysis reveals that these success stories may only

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sometimes be universally applicable and could sometimes paint an overly optimistic picture of the technology, given that some of these studies may have been conducted under controlled conditions or with significant financial backing, making it unclear how scalable or replicable these successes are for average farmers. In addition to this, focusing on success stories may overshadow the challenges and failures equally important for understanding the limitations of hydroponic systems, therefore, while case studies and success stories offer invaluable insights into the capabilities of hydroponic systems, a more nuanced and critical approach is needed to understand their broader impact, limitations, and the conditions under which they can be successfully implemented. Nevertheless, recent studies where different factors involved in soilless production are assessed becomes relevant to generate a big picture regarding the future of this field. In this sense, considering that soilless production can be limited by factors such as the availability of resources such as water, nutrients, and energy, as well as the cost and complexity of the system [45], several studies have reported the incorporation and analysis of technological advances in hydroponic systems over different crops and over different conditions, to overcome the limitations. Such is the case of [46], who carried out a study to assess the effects of other nutrient solutions on the growth and weight of two lettuce cultivars grown in a floating hydroponic system, indicating that hydroponic production can be cost-effective and easy option for organic vegetable production if the nutrient solution is managed according to the needs of the crop. In another case, [47] compared an aquaponic system, incorporating three different hydroponic systems to assess their effect on tomato yield, and morphological and biochemical impact quality, indicating that the choice of system had little effect over those properties, however, the system that incorporated drip irrigation presented slightly better results in terms of higher oxygen radical absorbance capacity, indicating the possibility of producing fruit with a higher health value. A study carried out by [48] analyzed the response of kale to liquid inorganic nutrients and different planting media in a DWC hydroponic system, indicating that there was a high effect over chlorophyll content and yield when using specific combinations of planting media and liquid inorganic nutrients. In another study on kale, [49] analyzed the effect of different nutrient-solution depths on the growth and phytochemicals accumulation in this hydroponic-grown vegetable to assess the issue of low dissolved oxygen in nutrient solution, indicating that there was a positive effect over kale growth when nutrient solution depth increased, where a 2-cm deep nutrient solution could promote kale growth, and 3-cm could have the potential of improving kale quality.

3. Substrate-Based Systems

3.1. Introduction to Substrate-Based Systems

In the context of soilless vegetable production, substrate-based systems offer an alternative to hydroponic methods, providing a unique set of advantages and challenges critical to understanding the advancement of the field. Unlike hydroponics, which relies solely on nutrient-rich water solutions, substrate-based systems use inert media such as coconut coir, perlite, or rock wool to support plant roots [45]. These substrates serve as a reservoir for nutrients and water, allowing for more forgiving management practices than hydroponics. This section introduces the fundamental aspects of substrate-based systems, including the types of substrates commonly used, their benefits, and the innovations shaping this method of soilless cultivation. As next-generation technologies evolve, substrate-based systems become increasingly sophisticated, incorporating automation, real-time monitoring, and data analytics to optimize crop yield and resource utilization. Therefore, understanding the intricacies of substrate-based systems is essential for researchers, practitioners, and policymakers who are invested in the future of sustainable and efficient soilless vegetable production.

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3.2. Substrate Materials and Their Benefits

In the rapidly evolving field of soilless vegetable production, the correct selection of substrate materials is a critical development that offers promising benefits but also presents challenges that require thoughtful analysis. On the positive side, newer substrates like biochar are sustainable and provide superior nutrient retention capabilities, also demonstrating exceptional nutrient retention, allowing for more efficient fertilizer use and reducing the environmental impact of nutrient leaching [50–53]. The advent of composite substrates, which combine different materials to optimize physical and chemical properties, adds another layer of versatility, offering tailored solutions for specific crop needs. However, these benefits often come at a cost—both literally and figuratively. Advanced substrates are generally more expensive than traditional options [44], making them less accessible for small-scale farmers. In addition to this, the availability of these new materials can be limited, especially in certain regions, which hampers their widespread adoption. Using new substrate materials also necessitates a learning curve, requiring adjustments in cultivation practices and additional expertise for optimal results. Moreover, while many of these substrates are promoted as sustainable options, the environmental impact of their production processes, including potential energy-intensive manufacturing and transportation emissions, should be considered [54]. An overview of some of the substrate materials in soilless agriculture is shown in Table 2.

Table 2. Overview of Substrate Materials in Soilless Agriculture, Highlighting Their Main Advantages and Disadvantages**.**

Substrate Materials	Main Advantages	Main Disadvantages
Coir	Renewable, excellent water retention, good aeration	Potential for high salt content, inconsistent quality
Perlite	Lightweight, good drainage, sterile	Expensive. Non-renewable, can float and cause uneven water distribution
Rockwool	Excellent water retention, sterile, easy to use	Non-biodegradable, manufacturing process has environmental impact
Vermiculite	High water retention, good nutrient-holding capacity	Expensive. Non-renewable, potential for compaction over time
Expanded Clay Pebbles	Reusable, good drainage, lightweight	High initial cost, potential for algae growth
Biochar	Renewable, improves soil structure, high nutrient retention	Variable quality, potential for high pH levels
Rice Hulls	Renewable, biodegradable, good aeration	Potential for pest issues, decomposes over time

Considering those above, it is important to highlight that, in the field of soilless vegetable production, substrate-based systems have evolved to include various materials and technologies, each with its own set of advantages and drawbacks that warrant a comprehensive comparative analysis. Newer substrates such as coconut coir and biochar offer superior water and nutrient retention capabilities and environmental benefits like biodegradability, however, these materials can be more expensive and require specialized management techniques [44]. Technological advancements have also led to the development of systems combining multiple substrates' benefits, offering tailored solutions for specific crop needs [45]. Furthermore, the choice of substrate can have implications for the system's environmental impact in terms of resource use and potential for waste generation. In this sense, while there is no one-size-fits-all solution, the choice of substrate and associated technologies in substrate-based systems should be guided by various factors, including cost, management complexity, crop-specific needs, and environmental impact.

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3.3. Innovations in Substrate-Based Cultivation Techniques

In soilless vegetable production, innovations in substrate-based cultivation techniques fundamentally alter the landscape, offering many advantages but presenting several challenges that require in-depth analysis. Automated nutrient delivery systems, for instance, are a game-changer, given that these systems are designed to directly provide precise amounts of nutrients to the substrate, thereby eliminating the guesswork and manual labor traditionally associated with fertilization [55]. The result is improved plant health and the potential for significantly increased yields, making this innovation particularly beneficial for commercial-scale operations [56]. Real-time monitoring technologies, often facilitated by advanced sensors embedded directly into the substrate, are another groundbreaking development. These sensors can measure various parameters, such as moisture levels, nutrient concentrations, and substrate pH, sending this data to a centralized system [38], meaning that growers can then make immediate, data-driven adjustments to their cultivation practices, optimizing resource utilization. This is a monumental step forward in terms of both sustainability and operational efficiency. However, the energy requirements for running these automated and monitoring systems should be more noticed. While they may optimize water and nutrient use, they also require a continuous power supply, which could increase the operation's carbon footprint if the energy is sourced from non-renewable resources [57,58].

4. Automation and Precision Farming

4.1. Role of Automation in Soilless Vegetable Production

Automation is increasingly becoming a focal point in soilless vegetable production, offering transformative benefits but posing challenges that require critical evaluation. Automation technologies, such as automated nutrient delivery systems [55], climate control [13], and robotic harvesting [59], can revolutionize the industry by increasing efficiency, reducing labor costs, and enhancing crop productivity. These systems allow for precise control over various environmental factors, from nutrient levels to humidity and temperature, enabling optimized growing conditions that lead to higher-quality produce. The data-driven nature of these technologies also provides valuable insights into crop performance, allowing for timely interventions and more effective resource management. The application of automation technologies into soilless vegetable production has been observed in studies such as the one of [60], who aimed to identify the optimal irrigation level in a microgreen production, based on the use of a dielectric moisture sensor, to finally generate a low-cost automated irrigation system, contributing to the automation of precision irrigation in hydroponically grown microgreens. In a similar study carried out by [61], a system for wireless irrigation management was developed and tested on soilless basil, concluding that employing a wireless sensor network to monitor substrate water conditions in real-time, along with detailed insights into how varying water availability impacts plants, proves to be a valuable resource for optimizing precision irrigation in soilless basil cultivation within greenhouses. In a study conducted by [62] about an automated system for fertigation control in soilless tomato growing in sand substrate under greenhouse conditions, concluded that the developed control system could effectively adjust fertigation cycle frequency according to plant transpiration, also reducing unnecessary applications under varying climatic conditions.

Based on the above, it should be noted that while automation holds great promise for improving efficiency and productivity in soilless vegetable production, it also introduces mainly financial and technical challenges that need to be carefully considered for a responsible and long-lasting adoption.

4.2. Application of Precision Farming/Agriculture Techniques in Hydroponics

In soilless vegetable production, applying precision farming or precision agriculture techniques to hydroponics and substrate-based systems is an emerging trend with far-reaching implications, given that precision agriculture is a tool able to generate an increase in production and quality, reducing the use of resources and the environmental impact [63]. These techniques, which leverage advanced sensors, data analytics, and automation, promise to optimize every aspect of the growing process, from nutrient delivery to environmental control. In hydroponic systems, for example, precision farming can lead to more efficient nutrient utilization, reducing waste and potentially lowering the environmental impact. Similarly, real-time monitoring can help fine-tune irrigation schedules and nutrient levels in substrate-based systems, thereby conserving resources and improving yield [64]. Several researchers have reported the use of precision farming applied to hydroponics. For instance, a study carried out by [65] developed a monitoring and controlling system in the context of hydroponic precision farming, based on the IoT concept and Fuzzy logic for the monitoring of water and nutrient needs of lettuce and bok choi, indicating that this monitoring system allowed to assess the needs of the crop in a timely manner, which translated into larger leaves for both crops. In another case, [66] proposed an automatic management system over a tropical hydroponic system, with the focus on reducing information exchange between sensors, obtaining a system that is simpler in terms of data obtention and analysis, being an aid in managing hydroponic crops. In a study carried out by [67] over a greenhouse with hydroponic crops, a low-cost sensor based in IoT to develop control processes on precision agriculture was developed, resulting in a series of benefits related to cost, energy saving, smart developing, and most importantly, an increase in acceptance by producers. Over a hydroponic saffron cultivation, [68] proposes a novel approach to sensor selection, aiming to optimize the cultivation of the crop in an artificial environment using technology, specifically IoT and sensors, creating an automated and controlled cultivation system.

In view of the above, it can be noted that implementing automation and precision farming techniques in soilless vegetable production presents a complex interplay of benefits and challenges that warrant a nuanced analysis. On the benefit side, automation and precision farming offer unparalleled advantages in terms of operational efficiency, resource optimization, and yield improvement. Automated systems can handle exact tasks like nutrient delivery and climate control, reducing human error and freeing up labor for other jobs. With its data-driven approach, precision farming allows for real-time adjustments to various growth parameters, leading to more efficient use of resources, such as water and fertilizers. This has the potential to increase yield and make the production system more sustainable by minimizing waste and environmental impact. However, these advantages come with challenges that must be addressed. As was mentioned before, the initial cost of implementing these advanced technologies, in addition to the energy consumption; can be significant, posing a financial barrier for small-scale farmers. This raises concerns about the equitable distribution of these benefits across the agricultural sector. These are concerns that need to be addressed properly and in a timely manner to fulfill the current needs for an increase in food production in a context of reduction in the cultivable surface and under the scenario of sever climate change.

4.3. Prospects and Trends in Automated Soilless Crop Systems

In the field of soilless vegetable production, the prospects and trends in automated systems are both promising and fraught with complexities that demand critical scrutiny. On the optimistic side, advancements the era of Agriculture 4.0 have been accompanied by technologies such as the IoT artificial intelligence, data analytics, big data, among others, which are able to generate tools that in the end can address issues such as food safety, data analysis and improved crop management [69]. These technologies will likely make soilless systems more efficient, scalable, and even self-adaptive, adjusting to environmental variables in real time for optimized crop yields. Integrating IoT devices could further streamline operations, allowing for remote monitoring and control, which is particularly beneficial for large-scale commercial setups. Sustainability is another area where automation could make significant strides, especially with the development of energy-efficient systems and closed-loop nutrient recycling processes. These technological advancements have transformed traditional farming methods into automated systems, introducing a new era of agricultural innovation driven by the IoT, fundamentally altering the way farming is conducted today [70]. In this sense, while the future of automated soilless crop systems holds immense promise for transforming the industry in terms of efficiency, scalability, and sustainability, the adoption of these systems should be done in a way that is equitable and responsible, considering the social and environmental impacts of the system [12].

5. Sensing and Monitoring Technologies

5.1. Importance of Sensing and Monitoring in Soilless Vegetable Production

In the evolving landscape of soilless vegetable production, the importance of sensing and monitoring technologies cannot be overstated, yet they come with their complexities that merit a critical examination. Sensing and monitoring technologies, such as soil moisture sensors, nutrient level detectors, and environmental sensors, are the backbone of data-driven agriculture [71–73]. They provide real-time insights into various growth parameters, enabling timely interventions that significantly improve crop yields and resource efficiency. For instance, soil moisture sensors can help optimize irrigation schedules, reducing water consumption. In this sense, [74] developed a cost-effective control system for the optimization of soilless crop irrigation through a prototype of an intelligent gravimetric tray that records the irrigation and drainage volumes and drainage pH and electrical conductivity (EC), as well as the temperature, EC, and humidity of the substrate. Regarding nutrient content, [75] determined the nutrient content of hydroponically cultivated microgreens with a novel immersible silicon photonic sensor to determine the optimal harvest time. These technologies are particularly crucial in soilless systems, where the margin for error is often smaller than in traditional soil-based agriculture. However, implementing these advanced sensing and monitoring systems is not without challenges. The initial cost of these technologies can be a significant barrier for small-scale farmers, and the data collected by these sensors often require sophisticated analysis, necessitating a level of resources and expertise that some farmers may not possess [76,77]. Ref. [77] found that one of the barriers to the adoption of agricultural innovations among farmers is the level of learning investment, initial investment cost and additional labor required when adopting a farm innovation, but also found that smallholder farmers continuously adapt to changing circumstances that affect their farming businesses, becoming age, gender, education level, years of farming and involvement in off-farm activities the influencing forces on the adoption of new technologies. These factors could limit or boost the adoption of these beneficial technologies.

5.2. Advances in Sensor Technologies for Nutrient Management and Environmental Control

In the domain of soilless vegetable production, advances in sensor technologies for nutrient management and environmental control are increasingly becoming pivotal, yet they introduce a set of intricate challenges that necessitate a thorough critical analysis. Cutting-edge sensors now offer unprecedented accuracy in measuring nutrient concentrations, pH levels, and environmental factors like temperature, moisture, and humidity [78]. This level of precision is a game-changer for soilless systems, where optimal nutrient and environmental conditions are crucial for maximizing yield and quality. For instance, nutrient sensors can automatically adjust the composition of nutrient solutions in real time, ensuring that plants receive exactly what they need for optimal growth. Ref. [79], developed an automatic system capable of performing water delivery automatically when the water level is less than a minimum predefined level and adding the nutrients automatically when the nutrient solution concentration is below 800ppm, using a GP2Y0A21 proximity sensor as a water level detector and a TDS sensor as a detector of electrical conductivity of the nutrient solution. In this system, a servo motor turns on a valve in the nutrient container. To improve macronutrient detection for a more efficient management of nutrients in crops growing under closed hydroponic, [80] developed a system based on ion-selective electrodes (ISEs) sensors, which can directly measure the analyte with a wide range of sensitivity, these being small and portable. The great benefit of this system is that it would allow the automatic sensing of nutrients in greenhouse hydroponics.

Environmental sensors can similarly adjust climate control systems to maintain ideal growing conditions. These advancements significantly reduce the margin for human error and can lead to more sustainable practices by minimizing waste of resources like water and fertilizers. For example, a researcher from Indonesia [81] built a simple micro-climate control system to control the temperature and humidity in a hydroponic lettuce greenhouse by implementing a Fuzzy Logic Controller based on pre-defined thresholds. Similarly, [82] presented an effective method that monitors and controls environmental parameters using sensors and actuators for tunnel farming and hydroponics, resulting in increased crop yield and water saving. A more comprehensive approach was taken by Chinese researchers [83], which developed an environment monitoring system for hydroponics and aquaculture applications. The system employed multiple sensors: dissolved oxygen and water temperature, outdoor meteorological parameters, soil temperature and humidity, indoor temperature, humidity and carbon dioxide concentrations, and humidity of hydroponic plant leaves. The data from these sensors is then transmitted to the cloud, processed, and displayed to the user through a web platform and a mobile application to support hydroponics and aquaculture production management. Another benefit of using sensors is what was proposed by [84] to estimate the condition of hydroponic tomato plants in real-time: they developed an environmental control system with wireless sensors that supply the appropriate amount of hydroponic liquid for the tomatoes based on evapotranspiration, with errors of less than 3%.

5.3. Real-Time Monitoring Systems for Optimizing Crop Growth and Resource Utilization

In the specialized field of soilless vegetable production, the advent of real-time monitoring systems for optimizing crop growth and resource utilization marks a significant leap forward, but it also brings forth a set of multifaceted challenges that require critical evaluation, considering, for example, that hydroponics necessitates more monitoring and micromanagement than traditional plant cultivation. Real-time monitoring systems, which often integrate various types of sensors and data analytics platforms, provide immediate feedback on a range of critical parameters such as plant development status, nutrient levels, moisture content, and environmental conditions [85]. This immediacy allows for dynamic adjustments that can significantly improve both yield and resource efficiency. With the aim to improve and automate the irrigation process in lettuce grown in a hydroponic system, [86] proposed a real-time monitoring system that considers the use of IoT technology for sensing important factors of the nutrient solution, such as pH, total dissolved solid (TDS), temperature and humidity. An application was developed that notifies the user of the parameters mentioned above and will initiate irrigation automatically through a click on the app. A different approach was taken by [87], where the application of computer vision in a smart system for real-time monitoring, quality control and condition assessment of romaine lettuce grown in aquaponic was researched. The proposed system uses image-processing techniques, image segmentation, deep learning, and regression analysis to estimate the size of the crops (growth rate) and then correlate it with their fresh weight, with the aim of be used in real scenarios to promote autonomous farms.

In nutrient film technique (NFT), two key parameters that affect plant growth are pH and EC. To maintain these parameters within a set range, [88] implemented a real-time fuzzy logic control for NFT-based hydroponic system using an IoT environment composed of a wireless sensor network, data logger and machine to machine actuators (pumps). With this system, they were able to stabilize the pH and EC values in less than 15 min. Table 3 summarizes different real-time monitoring systems.

Table 3. Overview of Real-Time Monitoring Systems for Optimizing Crop Growth and Resource Utilization, Highlighting Their Advantages, Disadvantages, and Key Metrics Monitored.

Real-Time Monitoring Systems	Advantages	Disadvantages	Key Metrics Monitored
Soil Moisture Sensors	Efficient water use, prevents overwatering	Initial setup cost, maintenance	Soil moisture levels
Nutrient Sensors	Optimizes nutrient delivery, reduces waste	High cost, calibration required	Nutrient concentration
pH Sensors	Maintains optimal pH levels, improves nutrient absorption	Calibration needed, potential for errors	pH levels
Temperature Sensors	Optimizes climate control,	Energy consumption, cost	Air and soil temperature

	improves yield		
Light Sensors	Efficient light use, improves photosynthesis	Initial cost, limited to certain crops	Light intensity, spectrum
Humidity Sensors	Prevents mold, optimizes water use	Calibration required, maintenance	Relative humidity
CO_2 Sensors	Optimizes plant growth, improves yield	High cost, complexity	CO_2 concentration

5.4. Case Studies Demonstrating the Effectiveness of Sensing and Monitoring Technologies

In soilless vegetable production, real-time monitoring systems and sensor technologies have shown promise in optimizing yield and resource utilization, as evidenced by various case studies. Countless systems that rely on different monitoring sensors, such as water level, pH, air humidity, air temperature, light intensity, CO_2 concentration, soil moisture and temperature, EC, among others, to then apply a smart decision workflow to control actuators, pumps, fans, lights, and other equipment with different levels of automation have been proposed and developed by [89–101]. However, while case studies often highlight significant improvements in yield and efficiency, they are usually conducted in controlled or well-funded environments, casting doubt on their generalizability to smaller operations. Additionally, these studies often focus solely on positive outcomes, neglecting to address challenges such as technical difficulties, ongoing operational costs, and data security risks. The energy requirements for these systems, if sourced from non-renewable resources, could also negate some of the sustainability benefits. Therefore, while real-time monitoring and sensing technologies offer groundbreaking opportunities for soilless vegetable production, their limitations related to cost, technical expertise, data security, and sustainability must be critically examined for a more comprehensive understanding of their long-term viability and equitable adoption.

6. Artificial Intelligence and Data Analytics

6.1. Integration of Artificial Intelligence (AI) in Soilless Crop Systems

Artificial intelligence (AI), referred as the simulation of human intelligence in machines that are programmed to perform tasks that typically require human intelligence, such as visual perception, speech recognition, decision-making, and language translation, comes to revolutionize the soilless crop systems by automating complex decision-making processes [102], optimizing resource allocation, and even predicting future growth patterns. AI algorithms can analyze vast amounts of sensor data to make real-time adjustments to nutrient levels, irrigation schedules, and environmental controls, thereby maximizing yield and minimizing resource loss [103,104]. However, this promising frontier also presents several challenges that require critical consideration, as can be seen in the Table 4.

Table 4. Overview of the Integration of Artificial Intelligence (AI) in Soilless Crop Systems, Highlighting Their Advantages, Disadvantages, and Key Use-Cases.

AI Applications in Soilless Systems	Advantages	Disadvantages	Key Use-Cases
Predictive Analytics	Optimizes yield, reduces waste	High setup cost, data quality issues	Yield prediction, disease detection
Machine Learning Algorithms	Adaptive, improves over time	Complexity, requires expertise	Nutrient management, climate control
Computer Vision	Real-time monitoring, high accuracy	Hardware cost, limited to certain crops	Disease detection, growth monitoring
Natural Language Processing (NLP)	User-friendly interfaces, easy monitoring	Limited capabilities, language barriers	User interaction, data interpretation

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Robotics and Automation	Labor-saving, high efficiency	High initial investment, maintenance	Harvesting, planting, pruning
IoT Integration	Centralized control, real-time data	Security risks, connectivity issues	Sensor data aggregation, remote control

6.2. AI-Based Decision Support Systems for Optimizing Cultivation Parameters

Using AI-based decision support systems in soilless crop systems offers a transformative approach to optimizing cultivation parameters such as nutrient levels, irrigation timing, and environmental conditions. These systems can analyze large datasets, identify patterns, and make predictive recommendations, thereby enhancing yield and resource efficiency [105–107]. AI has played a crucial role in transforming agriculture and protecting it from various threats such as weather, population growth, labor issues, and food security concerns. The numerous applications of AI in agriculture, including tasks like irrigation, weeding and spraying are often implemented through sensors in robots and drones. These technologies help conserve water, reduce pesticide and herbicide use, preserve soil fertility, and optimize labor, ultimately leading to increased agricultural output and improved quality [108].

In this regard, [109] presented the development and implementation of a smart agriculture IoT system based on deep reinforcement learning (DRL). The system consists of four layers: agricultural data collection, edge computing, agricultural data transmission and cloud computing, integrating advanced information technologies, including artificial intelligence and cloud computing, with agricultural production to increase food production while reducing the consumption of resources. The AI model technique used in the cloud layer is the DRL, for making immediate smart decisions, such as determining the amount of water needed for irrigation to enhance crop growth.

In an innovative way, the research made by [110] discusses the results of an international competition focused on autonomous greenhouses that aimed to combine horticultural expertise with AI to improve fresh food production with fewer resources. In this competition, five teams were assigned a cucumber greenhouse, which they had to control remotely for 4 months by applying their own AI algorithms, which varied between supervised, unsupervised, and reinforcement machine learning (Dynamic Regression, Deep Reinforcement Learning DRL, Deep Deterministic Policy Gradient DDPG, Generative Adversarial Networks GAN, Convolutional Neural Networks CNN, Recurrent Neural Networks RNN), according to data provided by different sensors, which allowed them to modify the heating, ventilation, screens, lighting, fogging and CO_2, water and nutrient supply. The results showed that with the use of AI it is possible to outperform the manually grown reference.

As a way to optimize the operation of AI technologies for agriculture, [111] proposed a novel approach using AI-based soft sensors combined with remote sensing models utilizing deep learning architectures. The study involves preprocessing techniques to handle missing data, clean and remove noise from agricultural land images. Feature representation is accomplished through a weight-optimized neural network with maximum likelihood (WONN_ML), followed by a classification process utilizing an ensemble architecture of stacked auto-encoder and kernel-based convolution network (SAE_KCN). The results show a 56% reduction in computational time, 98% accuracy, 85.5% precision, 89.9% recall, and an F-1 score of 86%, demonstrating the effectiveness of the proposed technique in agricultural applications.

These technologies are used to reduce the cost as well as increase the effectiveness and efficiency of agricultural practices [112].

6.3. Potential Challenges and Ethical Considerations in AI-Driven Cultivation

However, some related aspects must be considered when analyzing this technological advancement. First, the effectiveness of AI-based decision support systems depends on the quality and quantity of data they are trained on. The potential for algorithmic bias also exists, especially if the data used to train these systems does not represent diverse growing conditions and crop types. Poorly trained systems can lead to incorrect recommendations, potentially harming crop yield and wasting resources [113–115]. Second, the technical complexity of AI systems often requires specialized expertise to set up, operate, and interpret, creating a knowledge barrier for some farmers [116]. Finally, the increased reliance on digital technology introduces new vulnerabilities, such as susceptibility to cyberattacks, including data breaches and unauthorized system manipulation, that could compromise the data and have severe consequences for individual farmers and the broader food supply [117–119]. Therefore, while AI-based decision support systems hold immense promise for optimizing cultivation parameters in soilless agriculture, they also present challenges related to cost, data quality, expertise, ethics, and security that must be critically evaluated.

7. Environmental Sustainability and Resource Management

7.1. Role of Next-Generation Technologies in Enhancing Sustainability

Next-generation technologies, including AI, real-time monitoring systems, precision agriculture, and predictive analytics, promise to enhance sustainability in soilless vegetable production (Table 5). These technologies can optimize resource and energy use, reduce waste, and improve yield, contributing to economic and environmental sustainability [120]. For example, new applications of existing technologies, such as AI and mathematical models, have been successfully applied to predict energy consumption in agricultural applications, facilitating the evaluation of each component of production and leading to a reduction of CO_2 emission [121]. Also, real-time monitoring can facilitate precise irrigation and nutrient delivery, minimizing water and fertilizer use, such in [122] where they developed an irrigation control system for soilless culture based on a Proportional Integral Derivative (PID) algorithm that allows the fully automatic operation with a minimum set of variables, calculating the average daily leaching fractions reasonably well, to reduce the cost. In [123] a review on IoT implementations for real-time monitoring, control, and management in aquaponics (a closed-loop and soil-less method of farming) is presented. The importance of monitoring water variables is highlighted, such as water level, temperature, pH, dissolved oxygen, ammonia, nitrification, nitrites, electrical conductivity, Total Dissolved Solids, salinity and water hardness, and environmental variables, such as light intensity, relative humidity, air temperature, media moisture and CO_2. In addition to this, the study discusses wireless monitoring with the integration of sensors and communication technologies and the implementation machine learning techniques.

A key point to precise irrigation in this closed system is the estimation of crop evapotranspiration (ET_c). In this regard, [124] generated artificial neural networks (ANN), utilizing climate data from sensors (air temperature, relative humidity and solar radiaton), calculated inputs (crop coefficient and net radiation) and inputs from time and space (day of year, days after planting and extraterrestrial radiation), to create models for ET_c estimation over Tomato (cv. Duru) plants grown in two substrates (perlite and coco fiber) in an unheated plastic greenhouse. When the models generated were compared to traditional methodologies, such as FAO Penman-Monteith (PM) and Hargreaves (HG) equations, it was found that even with limited data, ANN models predicted ET_c better than classic equations, requiring only temperature and humidity sensors. Searching for similar results, [125] follow a dynamic Bayesian approach to modeling crop coefficient (Kr) and predicting crop ET for greenhouse sweet basil grown in soilless substrate, using input data from sensors measuring temperature, global radiation, and crop weight, connected to a lightweight IoT client operating in real-time. The results showed that the Kr approach predicts crop evapotranspiration with much higher accuracy than the Baille based ET (a simplified version of the PM equation proposed by [126] for greenhouses) approach does.

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Table 5. Overview of the Role of Next-Generation Technologies in Enhancing Sustainability.

Next-Gen Technologies	Advantages for Sustainability	Potential Drawbacks	Key Areas of Impact
AI and Machine Learning	Resource optimization, waste reduction	Energy consumption, data privacy	Water and nutrient management
IoT Devices	Real-time monitoring, energy efficiency	Security risks, e-waste	Climate control, irrigation
Blockchain	Traceability, transparent supply chain	Complexity, scalability issues	Food safety, environmental impact
Renewable Energy Sources	Low carbon footprint, long-term cost savings	Initial setup cost, intermittency	Energy supply for systems
Drones and Robotics	Reduced labor, precision agriculture	High initial cost, regulatory hurdles	Planting, harvesting, monitoring

7.2. Efficient Water and Nutrient Management Strategies

Efficient water and nutrient management strategies are pivotal in soilless vegetable production, offering the dual benefits of resource conservation and improved crop yield, emphasizing the environmental benefits of using inorganic substrate (rock-wool and volcanic tuff) and the reuse of nutrient solution (closed systems) to avoid water and nutrient losses [127]. Also, advanced sensing technologies, including smart irrigation systems and the utilization of surface reflectance data obtained from crop canopies, offer promising avenues for enhancing the efficiency of soilless farming systems. Utilizing cloud-connected wireless sensor networks to monitor real-time substrate water status in basil, [128] was able to automate irrigation and allowed assessing the physiological responses of plants to different water availability levels in the growing substrate. For an efficient crop management, it is crucial to detect early signs of water deficit stress. In this sense, non-contact techniques for detecting changes in spectral reflectance have been used successfully for monitoring water status of crops, as in tomato, where [129] found that crop reflectance increased with increasing water deficit or in [130], where spectral reflectance indices (SRI) allowed estimating the midday stem water potential in grapevines with great success. This demonstrates that smart irrigation systems become valuable instruments for precision irrigation management in soilless crop cultivation within greenhouses. When coupled with precise data regarding the impact of different water availability levels on plant growth, these systems offer a powerful solution for optimizing crop irrigation.

These precision agricultural techniques rely on real-time assessments of crop water demands rather than adhering to rigid watering schedules. As a result, they hold significant potential for optimizing water and nutrient utilization within soilless farming setups [127]. Technologies such as drip irrigation systems and nutrient film techniques can significantly reduce water usage, while real-time monitoring and AI-driven decision support systems can optimize nutrient delivery [127,131–136]. Traditional EC and pH sensors provide insufficient information about ion imbalances in hydroponic solutions, which can lead to nutrient wastage or reduced yields. This is why it has been proposed the use of on-site ion monitoring systems based on ion-selective electrodes (ISEs) that can automatically calibrate sensors and measure the concentrations of individual ions (NO_3^-, K^+, and Ca^{2+}) in hydroponic solutions [134], allowing farmers to effectively oversee nutrient management in reused solutions by promptly identifying any imbalances that may arise in the nutrient ratios.

However, these advancements are not without challenges. The initial cost of implementing these technologies can be prohibitive for small-scale farmers, raising concerns about equitable access [137,138]. Moreover, the effectiveness of these strategies is highly dependent on accurate data and specialized expertise for system calibration and maintenance, which could be barriers for some growers. There's also the risk of over-reliance on technology, potentially reducing manual monitoring and adjustments vigilance. Ethical considerations also come into play, particularly regarding data privacy and ownership, as many of these systems require cloud-based data storage and third-party analytics platforms [139]. Additionally, while these strategies aim to be sustainable, the energy requirements for operating advanced water and nutrient management systems could offset some environmental benefits if the energy is sourced from non-renewable resources [140,141].

7.3. Energy-Saving Techniques in Soilless Vegetable Production

Energy-saving techniques, such as solar panels, energy-efficient lighting, and automated climate control systems, are increasingly integrated into soilless vegetable production to reduce operational costs and environmental impact. These technologies can significantly lower energy consumption and increase performance, thereby contributing to the sustainability of soilless farming practices [142–147]. The majority of current greenhouses utilize conventional materials on the facade and traditional technologies for heating, cooling, ventilation, air-conditioning, lighting, energy generating, and storing, therefore, by simply changing the design and materials of the greenhouse with novel energy-efficient, low-cost, and eco-friendly solutions, such as semi-transparent PV modules, vertical ground heat exchangers, solar assisted heat pump systems, windcatchers, vacuum tube windows, blue and red LEDs for lighting, among others, farmers can minimize their cost on cultivation and thus to maximize their profits, with payback periods from 4 to 8 years [145].

However, adopting these energy-saving techniques is fraught with challenges that warrant critical analysis. Cost: the initial investment required for these technologies can be substantial, making it difficult for small-scale or financially constrained farmers to adopt them. This raises questions about equitable access to sustainability-enhancing technologies. Applicability: the effectiveness of these energy-saving techniques often depends on geographic and climatic factors; for example, solar panels may not be as effective in regions with limited sunlight [148]. Reconversion: the transition to energy-efficient systems may require a reconfiguration of existing setups, which could be both labor-intensive and technically challenging. Specialized knowledge: while these techniques aim to reduce energy consumption, they often require a certain level of technical expertise for installation and maintenance [149,150], potentially creating a barrier for less tech-savvy farmers. And lastly, sustainability: the push for energy efficiency should not overshadow other sustainability considerations, such as water use and waste management, which are equally critical in soilless vegetable production [151,152].

7.4. Life Cycle Assessment and Eco-Friendly Practices

Life cycle assessment (LCA) and eco-friendly practices are becoming increasingly important in soilless vegetable production as a means to evaluate the environmental impact of various cultivation methods and technologies. LCA provides a comprehensive environmental footprint analysis, from resource extraction to waste management, offering valuable insights into areas for improvement [153–158]. Eco-friendly practices, such as using organic substrates and renewable energy sources, aim to minimize this footprint. For example, [154] reviewing substrates for use in urban farming, found that perlite has the highest environmental impacts because is a material obtained from open-pit mines, which necessitates substantial energy consumption and a lengthy transportation process. Moreover, horticultural and fruit crops are typically regarded as highly intensive and frequently require numerous inputs, including fertilizers, pesticides, and various other materials, and the benefit of one cropping system over another cannot always be established, as was described by [157] in strawberry cultivated in traditional mulched soil tunnel versus a soilless tunnel system, concluding that, in general terms, tunnel exploits more land and crop inputs (excluding pesticides), while the soilless more technology and building materials, thus, making it difficult to establish which system is more environmentally sustainable.

As stated, these analyses can be challenging, especially for smallholder farmers. Conducting a thorough LCA can be resource-intensive, requiring specialized expertise and access to extensive data, which may be prohibitive or nonexistent. Eco-friendly practices often involve an upfront investment, raising concerns about cost and equitable access to sustainable technologies. While these practices aim to be environmentally sustainable, their effectiveness can vary depending on local conditions, such as climate and soil quality, which may limit their applicability on a broader scale. The transition

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to eco-friendly practices may necessitate significant changes to existing systems and operations, which could be costly and disruptive.

8. Future Directions and Challenges

8.1. Promising Areas for Further Research and Development

In the context of soilless vegetable production, promising areas for further research and development include the integration of AI and machine learning for predictive analytics, the development more efficient and affordable sensing technologies, and the exploration of alternative, sustainable substrates [159]. These areas hold significant potential for advancing the field by improving yield, reducing resource consumption, and enhancing sustainability [160–163]. However, several challenges and considerations accompany these promising avenues. First, focusing on high-tech solutions like AI could divert attention and resources from low-tech but effective traditional practices, potentially widening the gap between large-scale and small-scale farmers [164]. Soilless farming, particularly in the context of traditional crops like rice, soybean, and wheat, has seen limited exploration when integrating new technologies, e.g., artificial intelligence. Surprisingly, there is a lack of research dedicated to harnessing the potential of AI in these basic crop cultivation methods. Many existing systems remain in the prototype stage, and their practical application in real-world agricultural settings remains largely conceptual, especially within the confines of greenhouse environments [120]. Second, while the push for more sustainable substrates is commendable, the long-term impacts of these materials on plant health and yield are not yet fully understood and warrant further investigation [159]. Third, the drive for innovation must be balanced with cost considerations and accessibility to ensure that advancements benefit a broad range of producers, including those with limited resources [165,166]. Fourth, as research delves into increasingly specialized areas, there is a risk of creating solutions that are so tailored they cannot be easily adapted for broader applications. Finally, all new technologies and practices must be evaluated for their immediate benefits and long-term sustainability, including their environmental, social, and economic impacts [167].

8.2. Regulatory and Policy Considerations for Next-Generation Technologies

The advent of next-generation technologies in soilless vegetable production necessitates a reevaluation of existing regulatory frameworks and policy considerations to ensure responsible and equitable adoption [168]. While these technologies offer transformative potential in yield, efficiency, and sustainability, they also raise complex regulatory challenges. One of the main concerns is the issue of data privacy and security, especially with the integration of AI and real-time monitoring systems that collect extensive data [169,170]. Regulatory guidelines must be established to protect farmers' data and intellectual property. The use of new materials and technologies, such as different energy sources, alternative substrates, and genetically modified crops, may require updated safety and environmental impact assessments [171,172]. standardization is needed to ensure that new technologies are compatible with existing systems and practices, facilitating broader adoption [173]. Equitable access to these technologies is a significant concern [174]; without policy interventions, there's a risk that only large-scale, well-funded operations will benefit, exacerbating existing inequalities in the agricultural sector. Also, ethics must be considered in policy frameworks, such as potential job displacement due to automation, which may require retraining and upskilling to transition to other industries [175].

8.3. Potential Limitations and Hurdles to Widespread Adoption

Several limitations temper the potential for widespread adoption of next-generation technologies in soilless vegetable production (Table 6). First and foremost is the cost issue; the initial investment for implementing advanced technologies like AI-driven monitoring systems, precision farming techniques, new materials, and alternative substrates can be prohibitively expensive for small-scale farmers. This financial barrier risks creating a technological divide in the industry, where only well-funded operations can afford to adopt these innovations [176]. Second, there's the challenge of technical complexity; the operation and maintenance of advanced systems often require specialized skills and training, which could be a significant hurdle for less tech-savvy farmers [177]. Third, the effectiveness of these technologies can be influenced by various external factors such as climate, geographic location, and market demand, limiting their applicability in certain contexts [178]. Fourth, regulatory and ethical considerations, including data privacy and potential job displacement [169,179], could slow down the rate of adoption. Fifth, if not sourced sustainably, the energy requirements for some of these technologies could offset the environmental benefits they aim to provide [180,181]. Lastly, there's the issue of social acceptance; farmers and consumers may be hesitant to embrace these technologies due to concerns about safety, data security, or ethical considerations [182].

Table 6. Overview of Potential Limitations and Hurdles to Widespread Adoption of Soilless Agriculture, Highlighting Their Impact, Possible Solutions, and Areas Affected.

Limitations and Barriers	Impact on Adoption	Possible Solutions	Areas Affected
High Initial Cost	Barrier to entry for small-scale farmers	Government subsidies, financing options	Infrastructure, technology
Technical Complexity	Steep learning curve, specialized skills required	Training programs, user-friendly technology	System management, data analysis
Regulatory Uncertainty	Compliance risks, lack of standardization	Development of industry standards, regulatory frameworks	Food safety, environmental impact
Energy Consumption	Sustainability concerns, operational costs	Renewable energy sources, energy-efficient systems	Climate control, lighting
Water Quality	Risk of contamination, nutrient imbalances	Water treatment systems, real-time monitoring	Nutrient delivery, plant health
Social Acceptance	Consumer skepticism, market adoption	Public awareness campaigns, transparent labeling	Market penetration, consumer trust

9. Conclusions and Final Remarks

The research paper provides a thorough and balanced investigation into the role of next-generation technologies in soilless vegetable production, emphasizing both their revolutionary capabilities and the multifaceted challenges that limit their widespread adoption. It commendably addresses the financial barriers that could create a technological divide, favoring well-funded operations over small-scale farmers. The paper also critically examines the technical complexities that necessitate specialized skills, thereby widening the existing knowledge gap among farmers. While the paper is strong in discussing ethical considerations such as data privacy and job displacement, it could benefit from a more in-depth exploration of the regulatory frameworks and international trade regulations that may need to be revised to accommodate these innovations. Ongoing work in this field should prioritize the development of cost-effective technologies and educational programs to make these advancements more accessible. Future research should also focus on the long-term environmental sustainability of these technologies, as well as a more granular understanding of their ethical implications. By addressing these critical areas, the research can contribute to a more holistic understanding of the challenges and opportunities, thereby facilitating the ethical and equitable implementation of next-generation technologies in soilless vegetable production.

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Conflicts of Interest:

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