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Hydroponics vs Aeroponics: A Comparative Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The increasing global population, urbanization, and limited arable land have intensified the need for innovative and sustainable agricultural practices. Soilless cultivation systems, particularly hydroponics and aeroponics, offer viable solutions by enabling precise nutrient management, reduced water usage, and enhanced crop productivity. This review provides a comprehensive comparative analysis of hydroponics and aeroponics, examining their principles, mechanisms, growth performance, resource efficiency, economic feasibility, environmental impact, and crop suitability. Hydroponics, which delivers nutrients to plant roots via water-based solutions, is widely implemented due to its adaptability, moderate setup costs, and ability to support a variety of crops. Aeroponics, in which roots are suspended in air and periodically misted with nutrient solutions, offers accelerated growth, superior nutrient and water efficiency, and higher yields, although it requires higher initial investment and technical expertise. The review also highlights technological innovations, including automation, IoT integration, nutrient monitoring systems, and AI-driven optimization, which are enhancing the efficiency and scalability of both systems. Despite these advantages, challenges such as high operational costs, technical complexity, crop-specific nutrient

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formulation, and equipment reliability persist, indicating areas for future research and development. The comparative analysis suggests that while hydroponics is suitable for commercial and small-scale farming with moderate investment, aeroponics is ideal for high-value crops, urban vertical farms, and research-oriented applications. Overall, hydroponics and aeroponics are poised to play a crucial role in sustainable agriculture, addressing food security challenges and optimizing resource utilization. Continued innovation, research, and policy support will be essential for maximizing their potential in modern farming practices.

Keywords: Hydroponics; aeroponics; soilless cultivation; sustainable agriculture; nutrient delivery; plant growth; resource efficiency.

1. INTRODUCTION

Due to the expanding global population, rapid urbanisation, and lack of arable land, conventional agriculture needs innovative farming methods to provide food security and reduce environmental impact. Traditional soil-based farming is under strain from land scarcity, water shortages, soil erosion, and climate change (Regmi et al., 2024). Hydroponics and aeroponics are practical soilless production methods (Jensen, 1999). They offer efficient, sustainable, and scalable solutions to meet fresh product demand. These cutting-edge agricultural techniques allow controlled environment agriculture, which allows us to produce food year-round with higher crop yields and better resource usage on less arable land. A method for growing plants without soil uses nutrient-rich water, hence the term "hydroponics" from the Greek words for "water" and "labour" (ponos). The nutrition film technique (NFT), deep water culture (DWC), ebb and flow, wick, and aerated beds optimise nutrient supply and root aeration for particular crops (AlShrouf, 2017). Modern soilless growing method aeroponics suspends plant roots in air and mists them with a nutrient-rich solution at regular intervals. This method gives roots more oxygen, develops plants faster, and uses less water than hydroponics. Though different in method, efficacy, and crop suitability, both technologies use pH, temperature, humidity, and nutrient composition monitoring to maintain ideal growing conditions.

This analysis compares hydroponics and aeroponics, including their concepts, technical advances, growth performance, resource efficiency, economic feasibility, environmental impact, and crop adaptation. Review examines and contrasts the two ways. Comparing and contrasting fresh case studies with the current literature may help us understand the strengths and shortcomings of these two systems and where we can go from here in terms of research. This form of analysis is crucial for researchers, legislators, and farmers seeking sustainable and effective farming practices due to modern agriculture's serious concerns. This research compares hydroponics to aeroponics for growth efficiency, resource use, and cost-effectiveness. When available, it will provide quantitative and qualitative insights. Second, it will weigh the pros and cons of both systems and discuss their practical applications and technological needs. Third, it will highlight research gaps and innovation opportunities to confidently optimise soilless cultivation systems. This study compares hydroponics with aeroponics to give information on two sustainable agriculture approaches that can enhance food production while minimising resource use and enhancing environmental sustainability.

2. HISTORICAL DEVELOPMENT

From rudimentary methods employed by ancient cultures to modern, high-tech commercial systems, soilless agriculture technologies reflect humanity's eternal quest for more efficient and environmentally benign farming practices. The Hanging Gardens of Babylon, Aztec floating gardens, and early Egyptian irrigation systems used hydroponics, one of the first soilless farming methods. Although primitive, these approaches showed that plants could thrive in nutrient-rich water or another medium without soil (Wimmerova et al., 2022). Modern hydroponics was developed in the 20th century because of curiosity and the desire to grow food better (Jones, 2016). UC Berkeley scholars William Frederick Gericke and Dennis R. Hoagland developed hydroponics in the 1920s and 1930s by theoretically and practically addressing plant nutrition needs. In the mid-20th century, many hydroponic systems were developed to improve crop productivity, root aeration, water and nutrient supply, and system design. NFT, DWC, and ebb-and-flow systems were examples. Hydroponics became popular for large-scale, controlled-environment farming in the late 20th and early 21st centuries, especially in the Middle East and big North American and European cities with little arable land.

Hydroponics has long been the gold standard for soilless culture, but aeroponics maximises growth efficiency and resource use (Barbosa et al., 2015). The 1980s saw Richard A. Stoner and Gerald Nelson officially introduce aeroponics. They introduced root-suspending plants in air and sprayed them with nutrients. This strategy was used to accelerate plant growth, reduce water and nutrient loss, and boost root oxygenation. In subsequent decades, aeroponic technological developments permitted more exact management of nutrient content, humidity, and root exposure, as well as hybrid setups, low-pressure and high-pressure mist systems, and automated monitoring solutions. These innovations are more resource-efficient than typical hydroponic systems and can produce leafy greens, fruits, and tubers (Sharma et al., 2018) . Hydroponics and aeroponics have advanced in research and commercialisation. Hydroponics has advanced commercial NFT and DWC systems, nutrient solution standardisation, and urban agriculture and vertical farms (Sail et al., 2024). NASA's 1990s space farming projects, commercial urban vertical aeroponic farms, and sensor and IoT technology to automate and optimise growth conditions are important aeroponics advances. This historical backdrop allows us to compare hydroponics and aeroponics for growth performance, efficiency, and sustainability, and it shows how scientific interest and practical necessity are driving soilless growing innovation.

3. PRINCIPLES AND MECHANISMS

Hydroponics uses plant roots in or near a nutrient-rich water solution to provide all the macro- and micronutrients needed for plant growth. Compared to soil-based farming, hydroponics can carefully manage nutrient content, pH, and moisture levels, which can greatly affect plant growth and output. Hydroponics uses water to feed nutrients directly to the root zone, reducing agricultural water use (Idoje et al., 2023). This maximises absorption. Each hydroponic system delivers nutrients and supports roots differently. A thin layer of fertiliser solution flows over plant roots in the fertiliser Film Technique (NFT) to sustain nutrient uptake and oxygenation. Plant roots suspended in oxygenated nutrient solutions can absorb nutrients efficiently in Deep Water Culture (DWC) systems with air stones or diffusers. Ebb and Flow systems (sometimes termed "flood and drain" systems) cycle nutrients and oxygen to encourage vigorous root development by flooding and draining the growing medium. Passive wick systems are suited for small-scale or low-maintenance applications. They use capillary action to transfer nutrient solution from reservoir to growth media (Singh et al., 2024). To maintain an ideal growing environment and minimise nutritional imbalances and root infections, check water nutrients, pH, temperature, and dissolved oxygen. Effective hydroponic water management. Hydroponic systems allow commercial and small-scale urban farmers to cultivate herbs, fruiting plants, and leafy greens.

Aeroponics involves dangling plant roots in air and misting them with nutrient-rich fluid at regular intervals. Aeroponics may maximise root oxygenation and supply fertiliser more accurately than hydroponics, resulting in faster growth, higher yields, and better water and nutrient utilisation. Aeroponic systems are mostly hybrid, low-pressure, or high-pressure mist systems. Low-pressure mist systems disperse nutritional solutions in large droplets at low pressure, making them appropriate for modest setups or study (Singh et al., 2024). High-pressure mist systems use pumps exceeding 40-50 psi to atomise the solution into small droplets for maximum nutrient uptake and root coverage. Hybrid aeroponic systems combine hydroponics and aeroponics features including substrate root support and nutrient misting to balance stability and efficiency. In aeroponics, roots are misted to maintain a thin layer of nutritious solution and constant air exposure. This reduces waterlogging and root rot and boosts root respiration and nutrient uptake. Aeroponics lets plant species be optimised by controlling fertiliser concentration, misting intervals, droplet size, and environmental conditions including temperature and humidity. Aeroponic farming grows seedlings, herbs, and leafy greens well. It has also been employed in space agriculture studies to enhance growth efficiency and minimise resource use (Thomas & Bose, 2023). Finally, soilless culture systems like hydroponics and aeroponics distribute nutrients precisely, promoting plant development. Hydroponics requires roots to be submerged in nutrient solutions, but aeroponics maximises root oxygen exposure while spraying nutrients. Hydroponics is easier to use at commercial scales, but aeroponics allows for faster growth and improved resource efficiency.

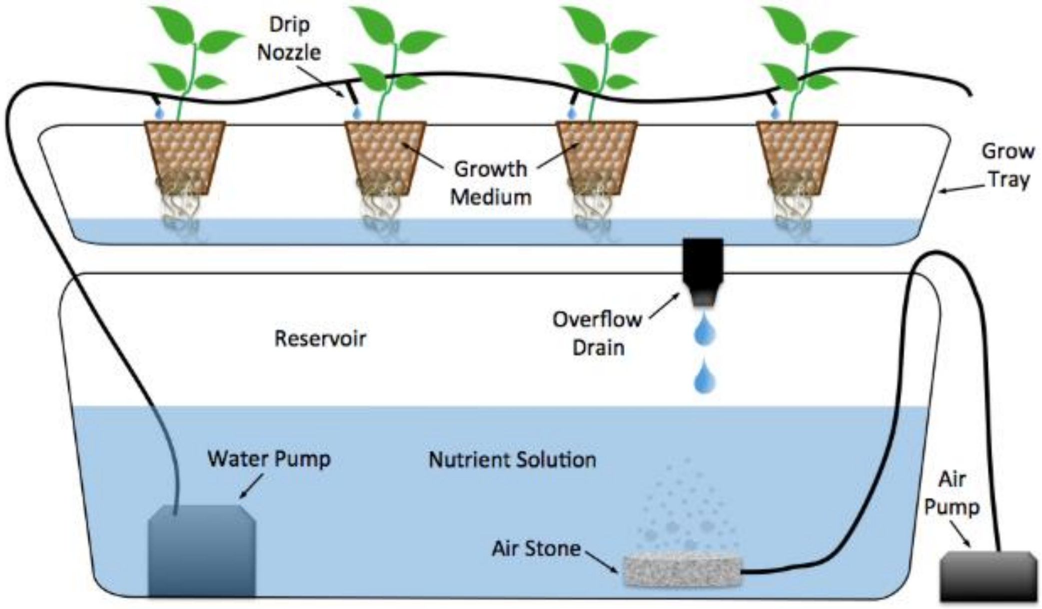

Fig. 1. Schematic of a hydroponic system

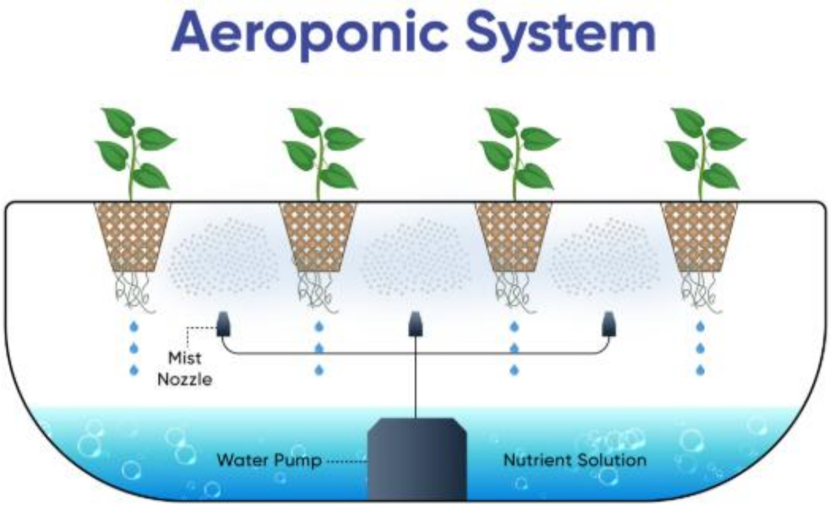

Fig. 2. Schematic of an aeroponic system

4. COMPARATIVE ANALYSIS

Hydroponics and aeroponics have pros and cons in different places. These include economics, crop suitability, growth rate, resource efficiency, and environmental impact (Faisal et al., 2024). Many studies show that aeroponic systems promote faster plant growth and productivity than hydroponic ones. Aeroponics' fine nutrient mist and high root zone oxygen availability optimise nutrient uptake, speeding growth, leaf area, and biomass development. Research on lettuce and spinach shows that aeroponic plants can outgrow hydroponic plants by 30–40% and yield more (Touliatos et al., 2016). Hydroponic systems produce great yields, especially when automated and supplemented with nutrients, although developing slower than traditional ones. Although less fast than aeroponics, nutrition film technology (NFT) and deep-water culture (DWC) can grow numerous tomatoes, cucumbers, and herbs (Garzón et al., 2023). Both systems exceed conventional soil-based farming in growth efficiency, although aeroponics is faster and can harvest earlier. Resource efficiency is another essential factor when comparing. Hydroponics uses much less water than conventional farming since it recycles and reuses water. Hydroponic systems require 70-90% less water than soil-based cultivation. Aeroponics saves 90-95% more water than normal farming by spraying nutrients directly to the roots (Weingarten et al., 2024). Both methods send exact formulas straight to roots to enhance nutrient uptake and reduce waste. Systems consume different amounts of energy. Hydroponic systems consume substantial quantities of electricity for water pumps, aeration, and lighting, while aeroponic systems, especially high-pressure mist systems, use a lot. Aeroponics' rapid growth and higher yields more than offset the extra energy used, improving resource efficiency.

When choosing between hydroponics and aeroponics, pricing is key. Commercial farms and small urban companies can profit from hydroponic systems' minimal setup costs and easy upkeep. Ebb-and-flow and wick systems are inexpensive and low-maintenance (Kumar & Verma, 2024). Aeroponic systems cost more but grow faster with pumps, misting devices, sensors, and automation. Due to its high-precision technology, aeroponics requires more work and time for maintenance. Aeroponics' quick growth cycles, greater yields, and possibility for higher market pricing boost ROI. High-value crops including herbs, microgreens, and specialised vegetables are especially affected.

Although both systems can be scaled up or down, hydroponics is still more frequent in commercial operations with a large footprint, while aeroponics is more common in research-oriented agriculture and high-tech vertical farms (Sadek & Shehata, 2024). Sustainable agriculture relies on hydroponics and aeroponics due of their environmental benefits. Both approaches enable urban controlled-environment farming while reducing land use and soil damage. Aeroponics uses less water and fertiliser than hydroponics, reducing its environmental impact. Vertical farming can result in local food production, reduced transportation emissions, and sustainable urban food supply chains (Benke & Tomkins, 2017). The two techniques suit different crops (Yıldız et al., 2018). Hydroponics can grow herbs, strawberries, cucumbers, tomatoes, and leafy greens due to its consistent yields and versatility. Aeroponics' high oxygenation and nutrient efficiency assist research and commercial nurseries' seedlings and transplants, as well as fast-growing, high-value crops like microgreens, basil, and lettuce. Aeroponics is ideal for vertical or intensive urban farming due to its shorter growth cycles and higher productivity per unit area, whereas hydroponics can efficiently produce enormous crops (Broćić et al., 2019). Finally, hydroponics and aeroponics are more efficient and sustainable than traditional farming. Aeroponics provides higher growth acceleration, water efficiency, and yield, yet hydroponics is easier to install, cheaper, and more predictable. Modern agriculture uses both systems, depending on crop type, resources, investment capability, and output intensity.

Fig. 3. Growth comparison or vertical farm example

Table 1. Crop suitability and yield comparison

Crop	Hydroponics Suitability	Aeroponics Suitability	Average Yield
Lettuce	High	Very High	3–4 kg/m²
Basil	High	Very High	2–3 kg/m²
Tomato	Very High	High	5–6 kg/m²
Spinach	High	Very High	3–4 kg/m²
Microgreens	Moderate	Very High	1–2 kg/m²

Table 2. The key advantages and limitations of hydroponics and aeroponics

Parameter	Hydroponics	Aeroponics
Growth Rate	Moderate, consistent growth	Faster growth, accelerated cycles
Water Efficiency	High (70–90% less than soil)	Very high (90–95% less than soil)
Nutrient Efficiency	High, precise control	Very high, rapid uptake
Setup Cost	Moderate, accessible for small and large farms	High, requires advanced equipment
Maintenance	Moderate, routine monitoring required	High, requires regular technical supervision
Energy Consumption	Moderate	High for high-pressure systems
Crop Suitability	Wide range of leafy and fruiting crops	Best for leafy greens, microgreens, seedlings
Yield Potential	High, consistent	Higher per unit area, faster cycles
Scalability	Easy for commercial operations	Suited for vertical farming and high-tech setups
Vulnerability	Root diseases, nutrient imbalances	Equipment failure, environmental sensitivity

5. ADVANTAGES AND LIMITATIONS

As advanced soilless gardening methods, hydroponics and aeroponics each have their own benefits and drawbacks that affect how they can be used in real life. A lot of people like hydroponics because it is easy to set up, flexible, and requires less money up front than aeroponics (Macwan et al., 2020). It gives exact control over the delivery of nutrients, pH, and water levels, which leads to higher crop yields and steady productivity. Hydroponics also uses a lot less water—up to 70–90% less than traditional farming on soil—and can be used in places where there isn't much usable land or the soil isn't very good. Its different system types, like ebb-and-flow, wick, nutrient film technique (NFT), and deep-water culture (DWC), can grow a wide range of crops, from leafy greens to fruiting veggies (Lakhiar et al., 2018). But hydroponics has some problems. For example, roots can get diseases, pumps and air flow need electricity, and the right mix of nutrients and water needs to be checked all the time. Large-scale hydroponic systems also need technical know-how and can have high running costs if robotic systems are added. Aeroponics, on the other hand, is better for growth efficiency, saving resources, and speeding up plant development. Aeroponics maximises oxygen exposure by misting roots with nutrient solutions. This helps roots absorb nutrients faster and often leads to shorter growth cycles and higher outputs than hydroponics. A lot less water is used (up to 90–95% less than standard farming), and nutrients are wasted less. As Pomoni et al. (2023) say, aeroponics works especially well for high-value crops, seedlings, microgreens, and vertical farming. It has been used successfully in both study settings and commercial urban farms. But there are some big problems with the system. Because they need pumps, misting systems, sensors, and automation tools, aeroponic systems cost more to set up at first. It takes more work to maintain because broken equipment or clogged mist tubes can really hurt plant growth. High-pressure aeroponic systems use more energy than hydroponics, and the method is sensitive to changes in the environment, so humidity, temperature, and the mix of nutrients must be carefully watched (Szepesi, 2023).

6. TECHNOLOGICAL INNOVATIONS AND TRENDS

As technology has gotten better, hydroponic and aeroponic farming have changed a lot. This has made modern farming more exact, efficient, and adaptable. Adding technology and the Internet of Things (IoT) to plants is one of the most important new ways to make them grow faster with less work and resources (Li et al., 2018). Keep an eye on things like light, temperature, humidity, and CO2 levels in the air to get the most out of your plants. This is possible with tools that automate things. The built-in Internet of Things (IoT) sensors can check on things like the pH level, the health of the plants, and the amount of water that is available all in real time (Mehra et al., 2018). These systems can make the best growing conditions with little help from a person because they automatically change the time of when nutrients are added, when plants are watered, and when they are misted. It's very helpful for vertical farms and big business farms with lots of things that need to be watched over by many people (Çalışkan et al., 2021). Another important technological advance in farming without soil is the use of nutrient monitoring tools. With the tools and equipment we have now, we can see in real time how much macro- and micronutrients are in hydroponic and aeroponic systems. These systems can tell when there are too many or too few nutrients and make sure that plants get the right amount of nutrients all the way through their lives. Smart dosing pumps change the nutrients right away when sensors send information in real time. The Thapa et al. (2024) say that these pumps are used in many current setups. It can help plants grow and produce more, and it can also save money, cut down on pollution, and stop fertiliser from going to waste.

These days, AI and ML are being used more and more in hydroponics and aeroponics to make the growing processes better. The AI can look through a lot of sensor data to guess how plants will grow, find possible threats like disease or stress, and suggest ways to make their growing conditions or food better. Computer vision systems can keep an eye on things like leaf colour, size, and shape to find nutrition deficiencies or pest infestations early on (López-Valdez et al., 2022). Machine learning models can use past data and crop-specific needs to find the best growth schedules, light cycles, and fertiliser formulas. This can increase system output and efficiency. When getting the most out of resources while still increasing production is very important, these AI-driven solutions really shine in high-tech vertical farms and research-based farming settings. It is expected that in the future, soilless farming will combine technology, ecology, and precision farming even more. To find a good balance between security and fast growth, scientists are looking into hybrid systems that use both hydroponics and aeroponics. Energy-efficient lighting, like LED systems with optimised spectrum output, is quickly becoming the rule in controlled-environment agriculture because it helps photosynthesis while using less electricity. Researchers are also looking into using green energy sources like wind and solar to make soilless farming last longer (Chaudhry & Mishra, 2019). Another area of study that gets a lot of attention is making bio-based nutrition solutions and eco-friendly substrates that have less of an impact on the environment. Self-driving systems and robots are getting better, which makes the idea of planting, monitoring, and harvesting without using your hands even more appealing. There would be a lot less work to do and costs would go down a lot. Finally, improvements in technology like automation, the Internet of Things (IoT) integration, nutrient monitoring systems, and optimisation powered by AI are changing hydroponic and aeroponic farms. These improvements allow for long-lasting, high-tech farming that can meet the needs of a growing world population (Farvardin et al., 2024). They also improve yield, economy, and the use of resources. At the point where technology, sustainability, and accuracy meet in soilless production, there are lots of opportunities for researchers, commercial farms, and urban farming projects.

7. CHALLENGES AND RESEARCH GAPS

There are information, money, and technology problems that make it hard for hydroponic and aeroponic systems to be widely used and work at their best, even though they have many benefits. Complexity of the system, dependability of the equipment, and management of the environment are the major technical problems. You still need to keep an eye on the pH, temperature, and oxygen levels in the solution, even though hydroponic systems are easier to set up than aeroponic ones. An imbalance in these factors could lead to a lack of nutrients, slow growth, or root diseases like Pythium-induced root rot. Because aeroponic systems don't have soil, they are very sensitive to equipment failures like nozzles getting clogged or pumps not working right, which can quickly hurt plant health. Both systems can break down mechanically or lose power because they need constant electricity and working infrastructure to keep the water moving, soaking, aerating, and controlling the environment. While sensors, internet of things devices, and artificial intelligence algorithms may make work more efficient, they also make things more complicated, which means that operators and support staff need to be trained. The money situation is another big problem. Hydroponics doesn't cost much to start, but it can get more expensive as automation and weather control technologies are added. It costs more to set up aeroponics because it needs pumps, misting systems, sensors, and automation equipment. Aeroponic maintenance costs are also higher than normal, especially for high-pressure systems that need to be watched all the time to make sure they don't stop delivering nutrients. Because of the high costs, soilless farming might not be possible for small farmers or stakeholders who don't have a lot of money. It might only work for large-scale business operations or urban vertical farms (Despommier, 2013). When thinking about using something on a big scale, it's important to think about how much it will cost. This is because using a lot of energy, especially in aeroponics and climate-controlled hydroponic systems, can make the costs go up even more.

Concerns have also been raised about the lack of knowledge about how nutrients are made and how crops can change. Not much research has been done on using hydroponics and aeroponics for staple crops, beans, and tubers. On the other hand, there is a lot of research on these topics for leafy greens, herbs, and a few fruiting crops. It's hard to get the best yields and system design because there isn't enough study on how different crops' roots react to different soilless systems and how their growth patterns change. Also, standardised nutrient mixes for different crops, locations, and system types have been made and will be made even better. It's still not clear how aeroponic misting frequency, droplet size, and nutrient concentration affect plant health for many economically important crops. This shows how important it is to do focused experimental studies. To lower costs and damage to the environment, using renewable energy sources could be explored. Also, automation and AI-driven decision-making could be looked into to make systems more efficient, and hybrid systems that combine hydroponics and aeroponics could be created. More plants can be grown without soil if scientists find new ways to combine nutrients, make growth media that is better for the earth, and find the best ways to make each crop grow better. Studies that look at these technologies' long-term economic viability, environmental sustainability, and social adoption barriers can give us the deep insights we need to make these technologies bigger. These gaps in knowledge, funds, and technological understanding need to be filled for hydroponic and aeroponic systems to live up to their promise of making farming more resilient and long-lasting.

8. CONCLUSION

New soilless gardening methods, such as hydroponics and aeroponics, have come up as good alternatives to traditional growing in the ground. They use resources more efficiently and produce more crops without affecting the environment. When you look more closely, it's clear that each way has its own benefits that are tailored to meet the specific needs of agriculture. Hydroponics is useful for commercial businesses, urban farms, and small-scale farmers because it is flexible, doesn't need a lot of money, and is easy to set up. Even though it costs more up front and needs careful technical management, aeroponics is clearly better for high-value crops, vertical farming, and research-based agriculture because it has faster production cycles, better growth rates, and more efficient use of water and fertiliser. Both methods help make farming more sustainable by using less water, managing nutrients more accurately, and relying less on land.

Aeroponics is more resource-intensive than hydroponics, which is more balanced and easier to scale up, but it makes better use of water and nutrients. Although aeroponics costs more to set up and run and needs a bigger original investment, it can produce higher returns for valuable crops. However, small and medium-sized growers can afford hydroponics. Both methods are good for the environment because they work with urban and vertical farming, reduce nutrient runoff, and keep the soil from breaking down. This shows how important they are for solving the problems in modern food production. It's possible for a wider range of plants to grow in hydroponics, but crop fit tests show that aeroponics is best for intensive cultivation because it grows microgreens, seedlings, and leafy greens quickly. These results lead to a number of ideas for researchers, politicians, and farmers. Before picking the best method, farmers should look at the types of crops they grow, the resources they have access to, their ability to make investments, and their operational knowledge. For growth to be more efficient and last longer, experts should look into hybrid systems, crop-specific nutrient optimisation, integrating renewable energy, and making monitoring better with AI. To get people to use hydroponic and aeroponic technologies, policymakers can offer financial incentives, professional training, and help with infrastructure. This is especially useful in places with few resources or that are in cities. In conclusion, hydroponics and aeroponics have the potential to change the farming business in ways that are better for the environment. These systems help fix the important issues of urbanisation, population growth, and environmental damage by reducing the need for fertile land, saving water, and making the best use of nutrients. More study, better technology, and laws that support soilless production will make it even more useful. This will solidify its place as a possible and necessary part of efforts to ensure global food security. Using automation, the Internet of Things (IoT), artificial intelligence (AI), and green energy solutions together can make farming more efficient and scalable, and it can also help farmers stay on top of sustainable farming practices. When these technologies are used correctly, they can help create a strong and long-lasting agricultural future by letting farmers and city managers grow nutrient-dense crops with little damage to the environment and by saving resources.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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