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Review Article

HYDROPONICS PER DROP MORE CROP FOR FOOD SAFETY: A REVIEW OF TECHNOLOGICAL PROGRESS AND CHALLENGES

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ABSTRACT

Hydroponics, a method of growing plants without soil, has emerged as a key innovation in modern agriculture, offering significant improvements in crop yields, resource efficiency, and sustainability. This review article explores recent advancements in hydroponic systems, comparing their performance to traditional soil-based agriculture, with a focus on yield improvements, water usage, and energy efficiency. Studies reveal that hydroponics can yield up to 30% more crops, particularly in high-demand varieties such as leafy greens and tomatoes, due to optimized nutrient delivery and controlled growing environments. Furthermore, the integration of renewable energy sources, such as solar power, has been shown to reduce energy consumption by up to 40%, making hydroponic systems more sustainable. This article also examines the role of automation, artificial intelligence (AI), and Internet of Things (IoT) technologies in enhancing the precision of nutrient management and environmental monitoring, resulting in greater efficiency and reduced labor costs. These innovations are driving the growth of hydroponic farming, presenting it as a solution to food security challenges and the environmental impact of conventional agriculture. This review is aimed at agricultural researchers, industry professionals, and policymakers, offering insights into how hydroponics can be leveraged to address the growing demands of sustainable food production in an increasingly resource-constrained world.

Keywords: : Internet of Things (IoT), hydroponics. Agriculture, sustainable food

1. INTRODUCTION

Hydroponics is a modern and innovative method of cultivating plants that eliminates the need for traditional soil-based agriculture [1]. Instead, it relies on a carefully balanced and nutrient-rich water solution to provide all the necessary elements for plant growth [2]. This technique has gained popularity in recent years due to its numerous advantages and potential for sustainable and efficient food production. In hydroponics, plants are grown in a controlled environment, such as a greenhouse or indoor facility, where factors like temperature, humidity, and lighting can be optimized for optimal growth [3]. The plants are typically placed in containers or trays, with their roots suspended in the nutrient solution, as illustrated in Figure 1. This allows the plants to absorb the necessary nutrients directly through their roots, without the need for soil as a medium [4].

all their required nutrients directly from the water solution, there is no need for excessive use of fertilizers or pesticides. This not only reduces the environmental impact but also minimizes the risk of soil contamination and water pollution. Additionally, hydroponics uses significantly less water compared to traditional farming methods, as the water can be recirculated and reused within the system. Another advantage of hydroponics is its ability to produce higher yields in a shorter time frame. By providing plants with an optimal growing environment and a constant supply of nutrients, they can grow faster and produce more harvests per year. This makes hydroponics particularly suitable for areas with limited arable land or harsh climates, where traditional agriculture may be challenging [8], as illustarted in Figure 2.

Figure 1 Hydroponic system

Figure 2 Hydroponics grown in trays

Hydroponics has a long history, dating back to ancient civilizations, one of the earliest examples of soilless plant cultivation comes from "The Hanging Gardens of Babylon" [5]. However, in the early 20th century William Frederick Gericke of the University of California was credited with popularizing the term "hydroponics" [6]. In the 1960s and 1970s hydroponics research expanded, driven by NASA's interest in growing food for space missions [7].

One of the key benefits of hydroponics is its ability to maximize resource utilization. Since the plants receive

Furthermore, hydroponics allows for precise control over plant growth and development. By adjusting the nutrient solution composition, pH levels, and lighting conditions, growers can tailor the environment to meet the specific needs of different plant species [9]. This flexibility enables the cultivation of a wide range of crops, including fruits, vegetables, herbs, and even flowers, all year round. Hydroponics also offers the advantage of reducing the risk of pests and diseases. Since the plants are grown in a controlled environment, the chances of infestations or infections are significantly lower compared to traditional farming [10]. This reduces the reliance on chemical pesticides and promotes healthier and more sustainable food production.

2. TRADITIONAL FARMING METHODS VS HYDROPONICS

When evaluating vertical farming, especially hydroponic setups, against traditional soil-based farming, several key aspects stand out, such as, yield efficiency, water usage, environmental impact, soil health, pesticide usage, and crop quality.

2.1 Yield efficiency

Traditional farming depends on the availability of arable land and is affected by seasonal variations, climate, and soil fertility [11]. Crop yields can fluctuate due to factors like drought, soil degradation, and pest infestations[11]. Although high-yield varieties and fertilizers have improved output, traditional farming typically does not reach the yield-per-acre efficiency of hydroponic systems. Whereas, hydroponic systems generally offer higher yield efficiency compared to traditional farming . According to [12], hydroponics can yield up to 30-50% more crops than soil-grown methods, primarily because plants grow faster due to optimized nutrient availability and controlled environmental conditions. Crops grown hydroponically can be cultivated year-round in indoor or greenhouse environments, which eliminates the challenges of seasonal changes and unfavorable weather, further boosting yield [12].

2.2 Water usage

Conventional agriculture is far more water-intensive. Crops are watered through irrigation or rainfall, but significant amounts of water are lost through evaporation, runoff, and soil absorption. In regions that rely on heavy irrigation, water use can be unsustainable, depleting local water sources [13]. In hydroponics, less water is consumed than traditional soil-based farming. Water usage is reduced by as much as 90% in some hydroponic setups due to the recirculation of water and nutrients in closed-loop systems [14]. Water lost through evaporation is minimal, and excess water is collected and reused.

2.3 Effect on environment

Traditional farming has a higher environmental impact due to soil depletion, erosion, and the use of large amounts of water, fertilizers, and pesticides. Over time, conventional farming can degrade soil quality, requiring more inputs (fertilizers, water) to maintain productivity [15]. Whereas, hydroponics has a lower environmental footprint in several areas. The controlled environments allow for more efficient use of resources, including water and fertilizers [16]. Since hydroponics is often practiced indoors, it does not contribute to soil degradation or erosion [16].

2.4 Soil depletion vs. Controlled nutrient delivery

Traditional farming relies on soil as the medium for plant growth. Over time, intensive farming practices can deplete essential nutrients from the soil, leading to soil degradation and reduced fertility. This necessitates the use of synthetic fertilizers, which can have negative environmental impacts, such as waterway pollution through nutrient runoff (eutrophication) [17]. In hydroponics, there is no soil involved, as illustrated in Figure 3. Plants receive nutrients through a carefully controlled solution, ensuring that they receive the exact amounts of nitrogen, phosphorus, potassium, and micronutrients needed for optimal growth [18]. Since nutrients are provided directly, there is no risk of soil depletion, and there is minimal nutrient waste. Plants can focus their energy on growth and development rather than nutrient scavenging, which leads to faster growth and higher yields [18].

Figure 3 Growing hydroponics without excess land area and soil

2.5 Pesticide usage and crop quality

Traditional farming, especially large-scale agriculture, often relies on pesticides and herbicides to manage pests, weeds, and diseases. This can lead to pesticide residues on crops and environmental contamination through runoff [19]. Hydroponic systems are typically conducted in controlled environments, such as greenhouses or indoor farms, where pests and diseases are easier to manage. As a result, hydroponic farming often requires little to no pesticide use, contributing to cleaner, healthier crops [20], feed for hydroponic cultivation is illustrated in Figure 4.


fig 4.

A detailed summary that delineates the comparative aspects of Hydroponics as opposed to Traditional Farming methodologies is meticulously encapsulated and presented within the confines of Table 1.

Table. 1 Hydroponics vs. Traditional Farming

Aspect	Hydroponics	Traditional Farming	References
Yield Efficiency	Up to 30-50% higher yields; year-round production	Dependent on seasons, soil fertility, and climate	[6], [21]
Water Usage	90% less water due to recirculation	High water usage; evaporation and runoff losses	[22]
Environmental Impact	Lower overall impact; no soil erosion; energy use	Higher impact; soil degradation, water overuse	[23]
Soil Depletion	None; controlled nutrient solution	Soil depletion and degradation over time	[23]
Pesticide Usage	Minimal or no pesticides in controlled environments	High pesticide use to manage pests and diseases	[24]
Crop Quality	Superior quality; fresher and cleaner produce	Varies; may have pesticide residues	[25]

3. Types of hydroponic systems

Hydroponic systems can be systematically categorized according to the specific methodologies they utilize for the efficient delivery of essential nutrients to the cultivated plants, thereby playing a crucial role in the overall effectiveness and productivity of the growth process in soilless agriculture [26]. In this context, Table 2 serves as a comprehensive resource that elucidates and juxtaposes the various types of hydroponic systems, providing a detailed analysis that facilitates a deeper understanding of their respective characteristics, advantages, and applications in modern horticulture. This comparative examination not only highlights the diversity within hydroponic practices but also informs practitioners and researchers alike about the optimal choices available for maximizing plant health and yield in controlled environments.

4. CURRENT TRENDS AND INNOVATIONS IN HYDROPONICS

4.1 Yield improvements

According to [33], significant yield improvements are shown in hydroponic systems compared to traditional soil-based agriculture. According to [33], hydroponic systems can produce up to 30% more tomatoes compared to soil-grown counterparts. This is attributed to optimized nutrient delivery and controlled growing conditions. Similarly, Hydroponically grown lettuce and other leafy greens often achieve higher yields and faster growth rates [34]. According to [34] study, yield increases of up to 50% in hydroponic systems due to more efficient nutrient uptake.

Table. 2 Different types of hydroponic systems

Hydroponic System	Nutrient Delivery Method	Best Used For	Advantages	Disadvantages	References
Wick System	Water and nutrients are drawn up by a wick into the root zone.	Small-scale, beginner-friendly systems, herbs.	Simple and low-cost.	Low efficiency. Not suitable for large plants with high water demand.	[27]
Deep Water Culture (DWC)	Roots are fully submerged in a nutrient rich water solution. Oxygen is provided by air pumps.	Leafy greens like lettuce, spinach, and herbs.	Fast plant growth.	Requires constant oxygenation. Unsuitable for large plants.	[28]
Nutrient Film Technique (NFT)	A thin film of nutrient solution flows continuously over the roots.	Commercial production of herbs, lettuce, and strawberries.	Minimal water and nutrient waste.	Pump failure can lead to quick root drying. Not suitable for larger plants.	[29]
EBB and Flow (Flood and Drain)	The grow tray is periodically flooded with nutrient solution, which then drains away.	Versatile, ideal for many types of plants, including tomatoes and flowers.	Highly effective for various plants.	Requires a timer and careful monitoring. Vulnerable to root rot if poorly managed.	[30]
Aeroponics	Nutrient mist is sprayed onto the suspended roots of the plants.	High-value crops, research, advanced setups.	Maximum root oxygenation. High nutrient absorption	High maintenance and technical precision are needed. Expensive setup.	[31]
Drip System	The nutrient solution is dripped slowly onto the roots through a tube or drip line.	Small to large-scale farming, especially for plants like tomatoes and peppers.	Versatile, and suitable for many plant types. Scalable for different sizes.	Requires periodic cleaning to prevent clogs in drip lines. Water waste if not recycled.	[32]

Hydroponics not only enhances yield but also improves crop quality and consistency. Hydroponic systems can produce crops with uniform size, color, and taste, as they are grown under controlled conditions that minimize variability [35].

4.2 Sustainability

Hydroponic systems are highly water-efficient. According to recent researchs, which indicates that hydroponics can use up to 90% less water compared to traditional soil-based agriculture [36]. The recirculation of water in hydroponic systems minimizes waste and optimizes water usage. Integrating renewable energy sources like solar power into hydroponic farms can significantly lower carbon emissions [36]. According to [37], combining hydroponic systems with solar panels can reduce energy consumption by up to 40%. These systems often include energy-efficient LED lighting and climate control mechanisms powered by solar energy [38]. Hydroponics generates minimal waste compared to traditional agriculture. The closed-loop systems recycle nutrients and water, reducing the need for chemical fertilizers and minimizing runoff [38].

4.3 Automation and AI

Advancements in AI and the Internet of Things (IoT) have revolutionized hydroponic farming. According to [39], recent developments in AI algorithms help in analyzing real-time data from sensors to adjust nutrient concentrations precisely, optimizing plant growth. Additionally, IoT devices continuously monitor environmental parameters such as temperature, humidity, and CO2 levels [39]. AI systems use this data to automatically adjust climate control systems, ensuring optimal growing conditions. AI-powered predictive analytics tools are being used to forecast crop yields, detect potential issues, and optimize resource allocation [40]. These tools analyze historical data and real-time inputs to provide actionable insights and recommendations. Automation in hydroponic farms includes the use of robotics for tasks such as planting, harvesting, and maintaining crops [41]. Robotic systems can handle repetitive tasks with high precision, increasing efficiency and reducing labor costs. Integration of various data sources, including sensor data, weather forecasts, and historical performance metrics, allows for comprehensive management of hydroponic systems [42]. AI models use this integrated data to enhance decision-making and improve overall farm performance.

4.4 Bioponics

Bioponics is a hybrid agricultural method that combines the principles of hydroponics (soilless farming) with organic farming practices [43]. While traditional hydroponics relies on synthetic nutrient solutions to feed plants, bioponics focuses on using organic and natural inputs for nutrient supply, making it a more sustainable and eco-friendly approach to soilless crop production [43]. In bioponics, organic fertilizers or nutrient solutions are derived from natural sources like compost teas, fish emulsions, worm castings, and organic plant residues. These nutrients provide essential minerals to plants without relying on synthetic chemicals [44]. Additionally, a vital aspect of bioponics is maintaining beneficial microbial populations. Microorganisms, such as bacteria and fungi, play a crucial role in breaking down organic matter and releasing nutrients in forms that plants can absorb. This creates a symbiotic relationship between plants and microbes, similar to what occurs in healthy soil ecosystems, enhancing nutrient uptake and promoting plant health [45]. Furthermore, Bioponics often incorporates organic waste recycling within the system. Organic matter, such as plant waste or biodegradable byproducts, is broken down and converted into nutrient-rich compost or teas that can be used as fertilizers [46]. This approach minimizes waste and promotes a circular, sustainable nutrient cycle.

4.5 Vertical farming

Vertical farming is an innovative agricultural method that involves growing crops in stacked layers, often within urban environments, to maximize space efficiency and optimize resource use [47]. This approach addresses the challenges of limited arable land and growing urban populations, offering a sustainable way to produce fresh food closer to consumers. In vertical farming, hydroponic setups are commonly used because they allow for soil-less cultivation in controlled environments, making them ideal for multi-level farming systems [48]. Vertical farming utilizes structures where crops are grown in vertically stacked layers or shelves, allowing a large number of plants to be cultivated in a small footprint [49]. This is particularly useful in urban areas where space is limited and land costs are high. Hydroponics, a method of growing plants without soil, is often the foundation of vertical farming. Plants are grown in nutrient-rich water solutions, with their roots suspended in water or a growing medium like coco coir or rock wool [50]. Vertical farms often operate in controlled environments, where factors such as temperature, humidity, light, and CO_2 levels are tightly regulated [51]. This ensures optimal growing conditions year-round, regardless of external weather or climate conditions.

5. CHALLENGES IN HYDROPONIC SYSTEMS

Hydroponics offers numerous advantages, such as efficient water usage, high yield, and the ability to grow crops in controlled environments. However, there are several challenges that need to be addressed for wider adoption and scalability.

5.1 Energy consumption

One of the biggest challenges of hydroponics is the initial investment required to set up a functioning system. Hydroponic farms need specialized equipment such as grow lights, nutrient delivery systems, pumps, and climate control mechanisms [34]. The cost of setting up these systems, particularly for large-scale operations, can be prohibitively high. For small-scale farmers or those in developing countries, these upfront costs can be a significant barrier to entry. Additionally, maintaining optimal temperature, humidity, and CO_2 levels requires significant energy for climate control systems [34]. In regions where electricity is expensive or unreliable, energy demands can be a major challenge.

5.2 Technical expertise

Hydroponics requires precise control over various factors, including nutrient concentrations, pH levels, water quality, light exposure, and temperature. Without proper management, crops can quickly suffer from nutrient deficiencies, overfeeding, or imbalanced pH levels [52]. Farmers must have a strong understanding of plant biology and nutrient requirements. The complexity of maintaining the ideal nutrient solution and continuously monitoring environmental conditions can be challenging, especially for individuals or organizations new to hydroponics [52]. The need for constant monitoring and the use of advanced sensors and IoT devices to track these parameters adds to the operational complexity [53]. This makes the system more vulnerable to failures if not managed correctly.

5.3 Scalability

While hydroponics has great potential for producing high yields in small spaces, it can be difficult to scale up the technology, especially in developing regions. The high capital investment required for infrastructure, coupled with the technical know-how needed, makes it challenging for smallholder farmers or those in regions with limited access to resources [54]. For hydroponic systems to become viable on a larger scale, particularly in regions where traditional agriculture is the norm, there needs to be a significant reduction in setup costs and increased access to affordable technologies [54]. In rural or underdeveloped areas, where access to electricity, clean water, and technology may be limited, the feasibility of setting up and maintaining hydroponic systems becomes more complex [55].

5.4 Dependency on technology

Hydroponics is heavily reliant on technology, from automated nutrient delivery to climate control and monitoring systems. Any technical failure, such as a pump malfunction, sensor failure, or power outage can quickly disrupt the delicate balance required for plant growth [56]. In traditional soil-based farming, crops can often survive short-term disruptions in water or nutrient supply. In hydroponics, however, the absence of soil means that even brief interruptions in nutrient or water flow can lead to rapid crop decline, making system reliability a critical concern [56]. Farms need backup power systems, regular maintenance, and contingency plans to mitigate the risks of technological failure.

5.5 Market access and consumer perception

For farmers looking to switch to hydroponics, accessing the market for hydroponically grown produce can be a challenge. While some consumers value the benefits of hydroponic crops (such as fewer pesticides and water use), others may be unfamiliar or skeptical of soil-less farming methods [57]. Hydroponic produce, which often comes at a higher price point due to production costs, can struggle to compete in markets where consumers prioritize cost over sustainability or innovation. In some regions, there are limited certification processes for hydroponically grown crops, making it difficult for farmers to market their produce as organic or environmentally friendly [57]. Consumer trust and regulatory approval are essential for the growth of the industry, and in many areas, these frameworks are still evolving.

6. FUTURE TRENDS AND THE ROLE OF HYDROPONICS IN GLOBAL FOOD SECURITY

Hydroponics is set to play a crucial role in addressing the challenges of food security, particularly in densely populated urban areas and regions facing harsh climatic conditions. As global populations rise and arable land becomes scarcer, hydroponic systems offer a sustainable solution to ensure reliable food production. Several trends are emerging that will shape the future of hydroponics and its role in global food security.

6.1 Projected Growth in Urban Hydroponic Farms

As the global population continues to shift toward urban centers, the demand for locally grown food will intensify. Hydroponic systems, especially vertical farms, are increasingly being seen as a solution to grow food within city environments, reducing the need for long-distance transportation and minimizing spoilage [58]. Urban hydroponic farms are expected to see significant growth, particularly in regions where real estate is at a premium. These farms maximize space efficiency by utilizing multi-level growing systems, allowing for more crop production in smaller areas. By growing food close to where it is consumed, urban hydroponic farms help address logistical challenges and reduce the carbon footprint associated with traditional agriculture [58]. The rise of vertical farming in urban areas is projected to increase exponentially in the coming years. This farming technique, which involves stacking layers of crops in controlled environments, allows cities to produce significant amounts of fresh food year-round, regardless of external weather conditions [59]. Advances in automation, AI, and IoT are enhancing the efficiency and productivity of urban hydroponic farms. Automated systems can monitor and adjust water, nutrient, and light levels, ensuring that crops receive optimal conditions for growth [58], [59]. This reduces the need for manual labor and improves scalability, making hydroponics more accessible for commercial-scale urban farms.

6.2 Hydroponics for combating food shortages in arid regions

Hydroponics is uniquely suited to regions with limited water resources, such as arid and semi-arid areas. Traditional farming methods are highly water-intensive, often leading to over-extraction of freshwater sources. In contrast, hydroponic systems can reduce water usage by up to 90% compared to conventional soil-based farming, as the water is recirculated within the system [60]. This makes hydroponics a potential solution for addressing food shortages in drought-prone regions or areas where climate change has disrupted traditional farming practices. By relying on controlled environments, hydroponics can provide consistent and reliable food production even in areas where natural growing conditions are not favorable [60]. In developing regions, where infrastructure for large-scale agriculture may be lacking, small-scale hydroponic systems can be deployed to support local food production. These systems require less land and can be operated in urban, peri-urban, or rural settings [61]. With proper investment and education, hydroponics could help communities in these regions grow nutritious crops, improving food security. Governments and international organizations are beginning to recognize the potential of hydroponics for sustainable development [61]. Supportive policies, investments in renewable energy, and capacity-building programs will be critical to scaling hydroponics in regions with limited resources.

6.3 Emerging technologies such as genetically engineered crops for hydroponic systems

The future of hydroponics may be significantly enhanced by the development of genetically engineered crops specifically optimized for water-based growing environments. These crops could be designed to thrive in nutrient-rich solutions, resist diseases, and yield higher-quality produce with less input [62]. Advances in CRISPR gene-editing technologies offer new opportunities for developing crops that are better suited to the unique conditions of hydroponic systems. For example, crops can be engineered to have faster growth cycles, improved root systems, or greater tolerance to fluctuations in nutrient levels and environmental factors [62]. These innovations could further improve the efficiency and sustainability of hydroponic farms, reducing the need for fertilizers and pesticides. In hydroponic systems, where nutrients are delivered directly to the plants through water, there is potential to further optimize this process using biotechnology [63]. Genetically engineered plants could be designed to absorb nutrients more efficiently, reducing waste and increasing yields. Additionally, the use of microbial consortia in hydroponic environments is gaining attention. These beneficial microbes could help improve plant growth, suppress diseases, and optimize nutrient availability, reducing reliance on synthetic inputs and creating more eco-friendly hydroponic systems [63].

7. CONCLUSION

In conclusion, hydroponics is a revolutionary method of growing plants that eliminates the need for soil and utilizes nutrient-rich water instead. With its numerous advantages, including resource efficiency, higher yields, precise control, and reduced risk of pests and diseases, hydroponics has the potential to revolutionize the future of agriculture and contribute to sustainable food production.

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