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Transforming Agriculture: A Comprehensive Review of Automated Hydroponic Systems

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Abstract

This review article delves into the potential solutions for the challenges posed by population growth and food scarcity. Traditional agricultural practices are struggling to keep pace with the increasing demand for food in a world where the population is reaching unprecedented levels. Automated hydroponics systems emerge as a promising alternative, offering plants a controlled growth environment without the need for soil. Within this review paper, we explore growth chambers, fertilizer-delivering systems, irrigation, and water management, as well as monitoring environmental conditions around the plants. Additionally, we examine conventional methods, various automated hydroponics technologies, and their associated data analysis techniques. Ultimately, the article evaluates the advantages and limitations of the technologies developed thus far and lays the groundwork for potential future research directions.

Index Terms: Automated system, hydroponics, food scarcity, urbanization, sustainability

1. INTRODUCTION

Food production and distribution in urban areas face substantial challenges due to high population density and limited access to arable land [1]. These challenges contribute significantly to ongoing global concerns about food insecurity [2]. Population growth and rapid urbanization have exacerbated the problem, making communities increasingly reliant on external food sources. Traditional farming methods become unsustainable in densely populated urban environments, necessitating alternative solutions to address food insecurity [1]. The current global population exceeds 8 billion people [3], and according to the Food and Agriculture Organization of the United Nations (FAO), it is projected to reach approximately 9.1 billion by 2050 [2]. Moreover, a substantial portion of this population is expected to have higher incomes, leading to increased demand for food in a society where education and awareness about the importance of nutrition for human development and health are widespread [3]. This population growth, coupled with changing dietary preferences and socioeconomic factors, influences the fundamental human need for sustenance. Meeting the growing food demand is a significant challenge, particularly in the context of the expanding global population and evolving consumption patterns. This article delves into the factors shaping food demand and their implications for food production, sustainability, and security. To anticipate food demand, projections for 2050 have been developed, considering various agricultural commodities and geographic regions. These projections consider scenarios involving socioeconomic development, climate change, and increased bioenergy utilization. The reference scenario (SSP2) predicts a growth of 59–98% between 2005 and 2050 [2].

Technological innovations have the potential to enhance food production by optimizing resource utilization, mitigating environmental impacts, and enabling year-round cultivation. These innovations offer a viable path to meet the rising demand for food while addressing challenges related to land availability, climate change, and water resources. With the world's population expanding and increasing food consumption increasing, the need for novel and sustainable food production practices has never been greater. Hydroponics, a soilless cultivation method where plants grow in nutrient-rich water solutions to create optimal growing conditions, has gained significant attention. This technology has revolutionized food production, offering numerous advantages over traditional soil-based agriculture [4][5]. Hydroponics is pivotal in sustainable agriculture, urban farming, and research as it effectively addresses food production challenges. Its potential to reshape our relationship with food and enhance our capacity for creative and resource-efficient plant cultivation will continue to grow as technology and knowledge advance. Hydroponics has gained popularity and diverse applications worldwide.

2. FOUNDATIONS OF HYDROPONIC AGRICULTURE: KEY PRINCIPLES AND PRACTICES

a. Pioneers and Milestones in Hydroponics History

Innovative experiments played a pivotal in accelerating the development of contemporary hydroponics during the 17th century, which was deeply rooted in its historical evolution [6]. Visionaries such as Francis Bacon and John Woodward conducted groundbreaking investigations into how plants thrive in water with nutrient solutions. Their work expanded our understanding of the essential components required for robust plant growth [7]. The field of hydroponics witnessed significant progress in the 19th century, thanks to the experiments conducted by Wilhelm Knop and Julius von Sachs. Their research laid the groundwork for in-depth studies on plant nutrition. In the early 20th century, William Gerick popularized 'hydroponics' and demonstrated the feasibility of cultivating crops using nitrogen solutions in a water-based environment [6].

b. Conventional Approaches to Hydroponic Cultivation

In the theoretical aspect of hydroponics, several techniques are employed in farming. Unlike traditional agriculture, hydroponics does not rely on soil for cultivating crops. Instead, this method involves the growth of plants on artificial or natural substrates, allowing their roots to efficiently absorb nutrients from a carefully prepared nutrient solution. The choice and application of specific hydroponic farming techniques can vary depending on factors such as the type of plant, regional climate conditions, financial constraints, and other considerations. Most hydroponic systems typically incorporate essential components, including an aerator and a tank for the nutrient solution

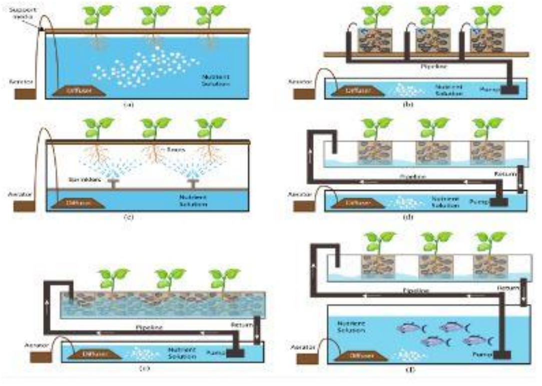

Figure 1. Different types of hydroponic systems. (a) Deep Water Culture. (b) Drip System. (c) Aeroponics. (d) Nutrient Film Technique (NFT). (e) Ebb and flow. (f) Aquaponics. [6]

Various innovative techniques have emerged in hydroponics, each with its unique approach to nourishing plants. Different types of hydroponics systems are illustrated in Figure 1. The Nutrient Film Technique (NFT) delicately sprays a nutrient-rich water layer over bare roots held on a sloping channel, with excess water returning to the reservoir [8]. This method is commonly used for cultivating herbs and leafy greens. Deep Water Culture (DWC) submerges plants into a world where their roots float in a nutritional solution, which is oxygenated through an air diffuser system, ensuring their flourishing whether on rafts or in pots [7]. Ebb and flow, also known as flood and drain, involves submerging plants in trays or containers filled with growing media, with an overflow system gracefully draining water, which then returns to the reservoir [8]. Aeroponics suspends plant roots in the air, and mists them with an appropriate nutrient solution, accelerating growth [9]. This is achieved through an efficient nutrient and oxygen delivery system in a closed-loop setup. Drip Irrigation provides each plant with a slow, continuous drip of nutrient solution, maintaining moisture in mediums like perlite or coconut coir, making it suitable for various crops [7]. Finally, Aquaponics combines aquatic life and lush greenery, where fish in a closed-loop water tank system provide essential nutrients to soil-less plants, creating a harmonious symbiosis in cultivation [6].

c. Nutrient Solution

The core of hydroponics, an innovative plant-growing method, revolves around the nutrient solution. In hydroponics, plants flourish without soil, depending on a carefully crafted liquid solution that contains all the necessary nutrients for their growth. Hydroponic systems provide numerous advantages over traditional soil-based agriculture, as they enable precise control over the nutrient composition, pH levels, and delivery methods [10], [11]. This section of the review article serves as an entry point to explore the intriguing world of hydroponics, which relies on nutrient solutions to cultivate robust and productive plants without the need for soil. Typically, the nutrient solution consists of a well-balanced blend of essential elements required for plant development. These include macronutrients such as sulfur (S), calcium (Ca), magnesium (Mg), potassium (K), nitrogen (N), and phosphorus (P). Additionally, it incorporates micronutrients like boron (B), molybdenum (Mo), zinc, copper, iron (Fe), and manganese (Mn), among others. The composition of this nutrient solution can be influenced by the specific hydroponic system in use, the crop being cultivated, its growth stage, and the precise formulation requirements [12].

Before being applied to the plant roots, the nutrient solution is usually diluted with water and carefully adjusted to achieve the appropriate pH level, which typically falls within the range of 5.5 to 6.5 for most crops. Diligent monitoring and maintenance of the pH and nutrient levels within the solution are crucial to promote optimal plant growth and overall health. It's important to note that different plants may require varying nutrient profiles depending on their type, growth stage, and environmental conditions. For the convenience of farmers, commercially available hydroponic fertilizer solutions are often pre-mixed and tailored for specific crops or growth stages [9].

3. AUTOMATED HYDROPONIC TECHNOLOGIES

Numerous researchers have incorporated robotic technologies to perform various tasks, ranging from planting to nutrient delivery [10], leading to increased overall efficiency [7] and reduced labor demands. Simultaneously, many researchers have utilized sensors to collect data on environmental conditions [13], nutrient levels, and growth indicators. Recent advancements in artificial intelligence have introduced advanced monitoring of nutrient delivery, growth conditions, health, and data analysis [14]. Wired and wireless communication technologies have facilitated seamless connectivity among various system components, with standard protocols such as Ethernet, Wi-Fi, and Bluetooth [14] employed for data sharing, remote monitoring, and managing automated hydroponics systems. The data generated by sensors and system components require storage, organization, and analysis through data management systems like databases and cloud-based platforms [15]. These systems facilitate trend analysis, data-driven decision-making, and system setting optimization, providing precise control over essential factors such as pH, temperature, humidity, light intensity, electrical conductivity, and water flow within the system [16]. They deliver nutrients and water with exceptional accuracy, reducing waste and enhancing resource efficiency. Requiring minimal human intervention and only periodic inspections, this approach saves valuable time. Automation plays a crucial role in maintaining consistent growth by mitigating fluctuations in environmental conditions [15], resulting in increased production, uniform plant development, and improved crop quality. However, it's important to note that the initial costs for sensors and control system components can be substantial [17], [18]. Despite their numerous advantages, automated hydroponic systems come with certain challenges and drawbacks. They necessitate technical expertise for both design and maintenance and are vulnerable to system errors or power outages [17].

Automated systems may also exhibit less flexibility compared to manual approaches, often requiring reprogramming or adjustments to adapt changes in cultivation methods, plant varieties, or experimental setups.

4. DATA COLLECTION AND ANALYSIS IN HYDROPONICS SYSTEMS

Data acquisition systems play a crucial role in the regulation of plant growth [13], [15], [19]. Typically, these systems utilize microcontrollers based on PIC or AVR, along with PLCs, to achieve precise control [13]. Monitoring essential parameters involves the use of sensors for humidity, temperature, electrical conductivity, pH, and light intensity [15], [19]. Furthermore, system development incorporates additional components like lights, water pumps, and fans [16]. Commonly used materials encompass iron, wood, or PVC [15], [20]. The integration of software solutions has ignited a revolution in automated hydroponics systems, facilitating precise management, monitoring, and optimization of crucial factors [20]. Effective techniques have been deployed to improve the efficiency of these systems [17], often incorporating LabVIEW graphical interface [16], PLC programming software like Haiwell Happy Programming Tool [17], and cloud software, along with IoT-based cloud platforms [21]. Despite these technologies providing advanced capabilities, challenges may arise in data analysis and hydroponics data collection, which can be complex [22]. Certain research has predominantly concentrated on one or two primary environmental factors within automated hydroponic systems [15], [16]. Nevertheless, to guarantee precise and healthy plant growth, it is imperative to comprehensively control all parameters and environmental conditions through hardware and software, as even a solitary mistake or miscalculation can result in crop failure. The key factors for assessing plant and system conditions encompass plant age, plant size (height), the rate of water flow through the system, and precise nutrient management by maintaining the pH and electrical conductivity of the water [23]

5. CONCLUSION

The review paper underscores the paramount significance of hydroponic systems in shaping our future world. It explains how we can integrate these systems with state-of-the-art technologies while ensuring minimal disruption to their upkeep. Understanding the intricate relationship between hardware and software integration is essential for everyone when it comes to automated hydroponics systems. This understanding lays the foundation for the progress of sustainable agriculture, unlocking the complete potential of hardware and software integration to improve food production, optimize resource utilization, and encourage more efficient and environmentally friendly farming methods. However, the automated hydroponic systems developed thus far require a forward-thinking outlook for their future development:

I. Numerous studies have not yet fully embraced the transformative potential of Internet of Things (IoT) technologies. Consequently, it is imperative to incorporate IoT for the purpose of facilitating uninterrupted data communication, sharing, and real-time monitoring.

II. Previous advancements should consider the integration of renewable energy sources to power hydroponic systems. By doing this, future innovations can make a substantial contribution to sustainability by providing environmentally friendly energy solutions.

III. A strategic transition toward vertical farming and urban agriculture, combined with the integration of automated technologies, has the potential to decrease transportation costs and improve the efficiency of food production and distribution

CONFLICTS OF INTERESTS

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The authors declare that there is no conflict of interest regarding the publication of this paper.

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