



The role of hydroponics in advancing eco-friendly agricultural practices

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Abstract

Hydroponics the practice of cultivating plants without soil has recently emerged as a cornerstone of sustainable agriculture. By utilizing nutrient-rich aquatic solutions rather than traditional soil, this method allows for superior resource management, including optimized water usage and meticulous control over pH levels and mineral intake. Because it enables high-yield production in constrained environments, hydroponics is an essential strategy for urban food security. Its popularity continues to surge globally across both industrialized and developing economies, largely due to its cost-effectiveness, reduced susceptibility to soil-borne diseases, and minimal environmental footprint. As the global population expands, hydroponic systems represent a vital technological advancement in securing a stable and resilient future food supply.

Keywords: Nutrition, plants, crops, vegetables, ecosystem, technique

Introduction

Biotechnology represents an expansive scientific domain that leverages biological systems or their components to engineer innovative solutions aimed at improving human welfare. These advancements span a wide spectrum of industries, with agriculture serving as a primary focal point—fittingly so, as it remains the economic foundation for the majority of developing nations (Sulemana and Adjei, 2015) ^[14]. Given that over 50% of the population in these regions relies on farming for their survival (du Toit and Neves, 2014) ^[5], the rapid global population growth necessitates the adoption of cutting-edge biotechnological methods. These modern approaches offer significant advantages over traditional farming, specifically by boosting crop yields and efficiency to meet rising food demands.

However, the expansion of industrial zones and urban sprawl has significantly reduced available arable land, leading to a subsequent drop in global food production (Van, 2009) ^[17]. In response, researchers have pioneered hydroponics a method designed to maximize agricultural output within constrained environments (Treffz and Omaye, 2016) ^[16]. Hydroponic cultivation involves growing plants in a nutrient-rich aqueous solution rather than soil. This solution is meticulously fortified with vital minerals including calcium, magnesium, and sulphur alongside essential micronutrients such as iron, zinc, manganese, and boron. This soilless approach has already demonstrated impressive success in the production of various crops, including cucumbers, tomatoes, spinach, lettuce, and leafy greens (Li *et al.*, 2018; Dhanasekaran and Jasmine, 2019) ^[4]. Sustainable agricultural frameworks prioritize ecological equilibrium to mitigate the ecological harm often associated with industrial farming methods. By integrating renewable energy solutions including solar, wind, and hydroelectric power these systems minimize their environmental footprint. Although modern agricultural technologies have successfully addressed the requirements of an expanding global population, they have concurrently accelerated the exhaustion of finite natural resources. Consequently, the adoption of sustainable practices has become a necessity to reconcile the demands of economic progress and human expansion with environmental stewardship. This

multifaceted approach aims to harmonize the economic, social, and ecological dimensions of food production through strategies such as agroforestry, vertical farming, organic cultivation, and Integrated Pest Management (Arumugam and Manida, 2023) ^[11].

History of Hydroponics

The term "hydroponics" is derived from the Greek roots *hydro*, signifying water, and *ponos*, meaning labor (Beibel *et al.*, 1960) ^[2]. The foundational literature on soil-less cultivation dates back to Francis Bacon's *Sylva Sylvarum*, published posthumously in 1627 (Ghatage *et al.*, 2019) ^[6]. Later, in 1699, John Woodward demonstrated through his work with spearmint that plants thrive better in water containing dissolved matter than in distilled water. By the early 1930s, William Gericke formally coined the term "hydroponics" to describe the method of nourishing plants by suspending their roots in nutrient-enriched water, optionally utilizing substrates like peat moss, perlite, coconut coir, or vermiculite (Jan *et al.*, 2020) ^[8]. Market analysts forecasted that the hydroponics sector would experience an 18.8% growth rate from 2017 to 2025, reaching a valuation of USD 490.50 million.

Why hydroponics

Projections indicate that by 2050, the human population will increase by 50%, while the global requirement for grain is set to double (Tilman *et al.*, 2002) ^[15]. This trajectory places immense pressure on conventional, soil-based farming, threatening the long-term viability of food security, natural ecosystems, and the management of urban and industrial growth. Compounding these issues, global soil health is deteriorating due to the combined impacts of climate instability, unpredictable environmental disasters, and the excessive application of synthetic agricultural chemicals.

To mitigate these risks and secure future food supplies, scientists have pioneered hydroponics a method of soilless cultivation. This agricultural innovation is gaining rapid traction across both industrialized and emerging economies, favoured for its cost-effectiveness, hygienic benefits, and minimal environmental footprint. In regions where high-quality farmland is scarce, hydroponics offers a versatile

solution, including application in high-altitude environments. Ultimately, as noted by Sahil *et al.*, (2023), adopting hydroponic systems provides a path forward to satisfy global nutritional needs by enabling the efficient production of diverse produce and livestock feed, all while promoting sustainable agricultural progress.

Hydroponic cultivation offers a wide array of advantages that make it a compelling alternative to conventional agriculture. Because these systems are not bound by seasonal changes, farmers can maintain consistent food production throughout the year, effectively maximizing output within a smaller physical footprint. This capability is particularly vital for locations where fertile ground is limited, including metropolitan centres, arid landscapes, or terrains plagued by depleted soil (Ping, 2023) ^[10]. Additionally, hydroponics grants growers' meticulous oversight of nutrient delivery; by customizing the feeding process, plants thrive more rapidly and reach greater sizes, ultimately resulting in more bountiful harvests compared to earth-based gardening.

Water efficiency serves as another primary benefit of the hydroponic approach. Given that agriculture consumes roughly 70% of the world's fresh water, as noted by the United Nations, the ability to conserve is critical. Hydroponic setups operate on recirculating systems, ensuring that moisture is reused and plants consume only what is necessary, which drastically minimizes evaporation and runoff. This trait is an essential solution for drought-stricken regions or areas facing severe water scarcity. Beyond resource management, hydroponics represents a more ecologically responsible path for food production. By moving away from traditional soil-based methods, the need for toxic herbicides and pesticides which frequently jeopardize human health and damage local ecosystems is largely removed. Furthermore, because these systems function without soil, they successfully mitigate issues like nutrient leaching and erosion, establishing a cleaner, more sustainable agricultural model (Ping, 2023) ^[12].

Types of Hydroponics

Wick system or Passive system

According to Yoeurn and Serey (2024), wick-based hydroponics offer an ideal, pump-free method for growing indoor flora. This passive design utilizes materials like nylon to transport nutrient-rich water to the root zone via capillary action. While these systems are popular in residential or office settings due to their uncomplicated nature, they are generally unsuitable for large or long-lived plants, as they struggle to satisfy the higher water demands of such vegetation.

The drip system

There are two primary categories of drip irrigation: recovery and non-recovery models. In a recovery setup, the water or nutrient solution is captured after use and cycled back into the main reservoir. While this approach requires diligent monitoring to prevent issues like pH fluctuations or the development of mold and algae within the plumbing and reservoir, many professionals prefer it over the non-recovery method. In contrast, the non-recovery system operates by dispensing solution once, which requires consistent manual oversight to guarantee that plants receive the appropriate amount of hydration and nutrients (Souza *et al.*, 2023) ^[13].

The ebb and flow system

Ebb and Flow hydroponics, a widely adopted soil-less growing technique, functions by cyclically submerging a plant's growth medium in a nutrient-dense solution before letting it recede into a storage tank. This rhythmic process serves a dual purpose: providing necessary sustenance while simultaneously aerating the root systems.

Historically, these systems relied on simple timers to manage irrigation, which frequently resulted in the unnecessary depletion of nutrient resources. In an effort to curb this waste, recent studies have introduced fuzzy logic controllers as a superior alternative. By integrating hardware like Arduino UNO microcontrollers, DC pumps, and sensors for both temperature and moisture, these systems can dynamically adapt irrigation schedules based on prevailing environmental data. According to Daud *et al.*, (2018) ^[3], utilizing this intelligent control method effectively fine-tunes nutrient distribution, drastically reducing resource loss while promoting more vigorous plant development.

The deep-water culture

Deep Water Culture (DWC) relies on keeping plant root systems permanently immersed in a nutrient-dense aqueous solution. Maintaining the correct fluid volume is vital for plant health; consequently, integrating an HC-SR04 ultrasonic sensor allows for real-time monitoring of reservoir levels. When the water retreats past a predetermined limit, the system triggers a 12V DC pump to replenish the supply. By utilizing a linear regression model to calibrate the exact pump activation duration, the system can regulate water levels with a precision accuracy of nearly 88%. Furthermore, the inclusion of an Android-based interface empowers users to manage nutrients and adjust settings remotely. As noted by Yoeurn and Serey (2024), such automation and remote oversight are highly effective for optimizing the DWC growing environment.

The nutrient film technique (NFT) system

The Nutrient Film Technique (NFT) is a hydroponic method characterized by a shallow, perpetual flow of nutrient-rich water over plant root systems. This configuration ensures that roots receive a balanced intake of hydration, essential minerals, and atmospheric oxygen. By recycling the nutrient solution, the system maximizes efficiency and prevents resource exhaustion. Furthermore, NFT significantly reduces water consumption compared to traditional soil cultivation. Because the roots are exposed to frequent aeration, plants typically exhibit accelerated growth rates and heightened yields. The soil-less nature of this technique also mitigates the risks associated with ground-dwelling pests and pathogens, making it an ideal, space-efficient solution for urban agriculture and greenhouse environments (Rusmayadi *et al.*, 2023) ^[12].

Substrates in Hydroponics

In hydroponic cultivation, the choice of substrate is essential for structural support and efficient nutrient uptake. Several traditional materials are widely used, each with distinct trade-offs:

- **Rockwool:** Often utilized for its reliability, though it is not biodegradable and poses respiratory risks due to dust.
- **Expanded Clay:** Prized for its superior drainage and oxygen circulation.

- **Perlite:** Favored for its lightweight structure and ability to improve aeration, despite having poor water-holding capacity.
- **Coconut Chips:** A highly sustainable, organic, and renewable alternative that excels at trapping moisture.
- **Phenolic Foam:** Offers impressive water retention and a lightweight profile but presents concerns regarding plastic waste.

According to Zhao *et al.*, (2022) [20], the industry is shifting toward more sustainable innovations. Modern substrates made from keratin (processed from feathers or hair) or cellulose (derived from wood pulp) are gaining traction. These materials effectively balance moisture retention with controlled nutrient release, providing a biodegradable and ecologically conscious base for modern hydroponic setups.

Advantages of Hydroponic Systems

Hydroponic cultivation facilitates accelerated crop development with minimal land and water consumption, yielding high-quality, sustainable produce. By providing nutrient-dense animal fodder, this method improves livestock health and productivity while lowering carbon footprints and eliminating the need for chemical pesticides. Although the initial capital investment is significant, the system is highly efficient, requiring little labor or ongoing expenditure once established. Despite challenges such as the necessity for specialized technical expertise, elevated seed costs, and the risk of waterborne or fungal pathogens, the adoption of hydroponic technology offers substantial agricultural advantages (Ghorbel *et al.*, 2022) [7].

Disadvantages of Hydroponic system

Hydroponic farming entails significant financial barriers due to the specialized infrastructure and equipment required for setup. Beyond capital investment, successful operation demands a high degree of technical expertise, as staff must possess a deep understanding of both plant physiology and mechanical systems. These systems are inherently fragile; technical malfunctions can rapidly lead to crop failure or severe plant distress. Furthermore, maintaining precise nutrient balances is an ongoing challenge, and the improper discharge of these mineral-rich solutions presents a notable ecological risk. The method is also limited by its inability to accommodate all plant varieties, which may require specific growing conditions, and its heavy reliance on advanced technology renders it unsuitable for regions with limited infrastructure or resources (Wiggins *et al.*, 2020) [18].

Conclusion

In summary, while initial capital investment and ongoing maintenance costs remain significant barriers for small-scale growers and those in emerging economies, these hurdles are gradually diminishing. Ongoing advancements in technology, coupled with global efforts to provide essential training and financial support, are helping to bridge this accessibility gap. Ultimately, hydroponics stands as a transformative solution to the limitations of conventional farming. By offering a resource-efficient and sustainable method for food production, it is poised to become a cornerstone of future agricultural strategy as it continues to evolve and become more widespread.

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