

Review Article

A Closer Look at Hydroponics and its Synergistic Technologies for Medium and Small-Scale Applications

Abstract

Hydroponics, the practice of soilless plant cultivation, has undergone significant transformation over the years, evolving from its roots in ancient civilizations to its modern, high-tech systems. This paper explores this journey, focusing on technological advancements that have not only refined the principles of hydroponics but have also democratized its accessibility. Early accounts of hydroponic-like practices can be traced back to the Hanging Gardens of Babylon, the Floating Gardens of the Aztecs, and historical records in China and Egypt. The formalization of hydroponics, however, took place in the 20th century, although the concept had been introduced much earlier by Sir Francis Bacon in 1627. Technological leaps in nutrient solutions have been pivotal; German botanists Julius von Sachs and Wilhelm Knop's work in 1860 set the scientific basis for soilless culture. Modern hydroponic systems such as Nutrient Film Technique (NFT), Aeroponics, and Deep Water Culture (DWC) employ pumps, timers, and nutrient reservoirs for efficient cultivation. These systems have scaled hydroponics from a lab-scale practice to a commercial-scale operation, making it accessible to both hobbyist gardeners and large-scale agriculturalists. Another transformative development is in the area of hydroponic lighting. High-Pressure Sodium (HPS) and Light Emitting Diode (LED) lights offer sustainable and efficient alternatives to natural light, thus enabling year-round, indoor hydroponic farming. The automation of hydroponic systems via computer-controlled environments has drastically reduced the manual labor required, making it accessible to individuals without specialized horticultural skills. Lastly, the paper delves into synergistic technologies like smart monitoring systems, Internet of Things (IoT), and renewable energy sources that are setting new paradigms for hydroponics. Smart sensors and analytics provide real-time data for nutrient and environmental control, while IoT devices offer remote management capabilities. Renewable energy sources like solar and wind power bring sustainability to hydroponic setups, thereby reducing the carbon footprint. These technologies collectively create an environment that is conducive not just for optimal plant growth, but also for operational sustainability and efficiency.

Keywords: *Hydroponics, Technology, Automation, Sustainability, Nutrients*

1.0 INTRODUCTION

The art and science of plant breeding have undergone remarkable changes in recent years, largely due to the introduction of advanced genetic tools such as **Clustered Regularly Interspaced Short Palindromic Repeats** (CRISPR), Genomic Selection, and Marker-Assisted Selection (MAS). CRISPR allows for the precise editing of specific DNA sequences, enabling the targeted

modification of genes linked to desired traits. It has revolutionized plant breeding, medicine, biotechnology etc. Genomic Selection uses statistical models to predict the genetic merit of plants at an early stage, thus accelerating the breeding process, as illustrated [1]. This technique can significantly reduce the time needed for breeding cycles, aiding in quick adaptation to challenges like climate change. Similarly, Marker-Assisted Selection (MAS) employs DNA markers closely linked to desired traits for early selection, improving both the speed and precision of breeding programs. These modern tools have not only made the process more efficient but also more accurate. For instance, CRISPR allows for the isolation and modification of specific genes responsible for traits like drought resistance, without altering other traits, a precision that was largely unachievable with traditional methods [2]. MAS further contributes to this by allowing early selection based on molecular markers, thus conserving resources that would otherwise be invested in less promising plants. Moreover, these new genetic tools have helped overcome natural limitations, such as species barriers, that constrained traditional plant breeding. CRISPR technology allows for gene transfer between distantly related plants, fundamentally expanding the pool of genetic diversity [3]. Genomic Selection and MAS have also facilitated the use of 'exotic' germplasms or genetic material from wild species, further broadening the horizons for new plant varieties.

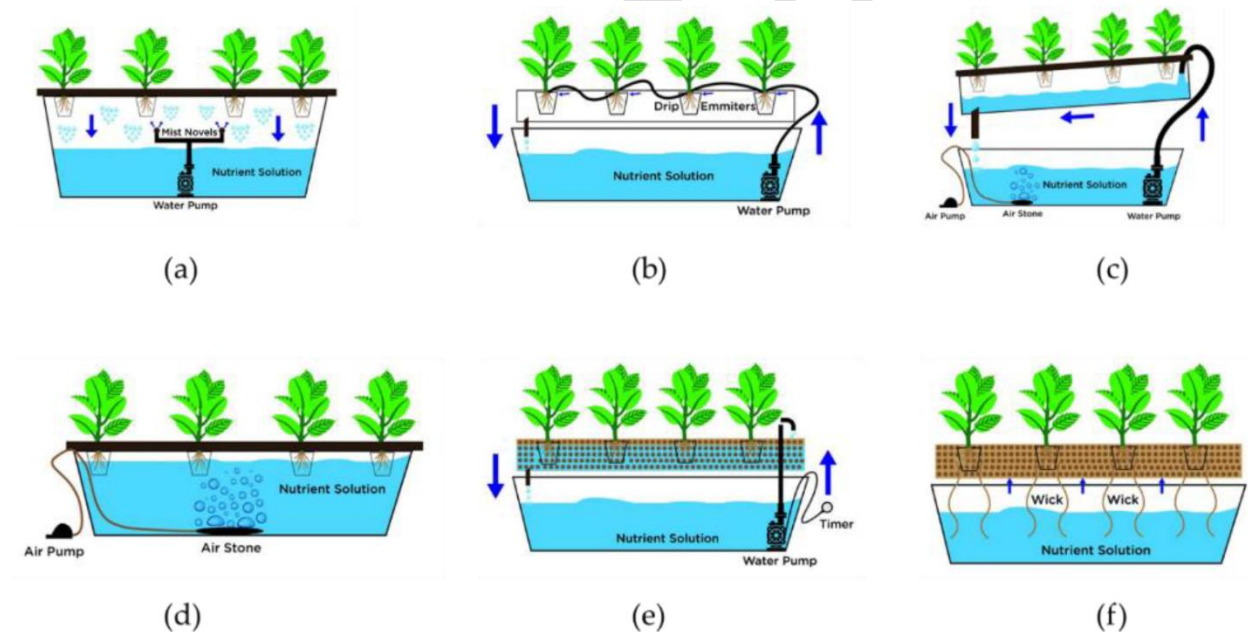


Figure 1: Common hydroponic systems: (a) aeroponics, (b) drip system, (c) nutrient film technique (NFT), (d) deep water culture, (e) ebb and flow and (f) wick system.

1.1 Historical Background

The history of hydroponics stretches from ancient soil-less cultivation practices to today's technologically advanced systems, representing a confluence of enduring principles and modern innovations. The idea of soil-less cultivation predates the term "hydroponics," with its early roots

evident in ancient civilizations such as the Babylonians, Aztecs, Chinese, and Egyptians. Whether it was the speculative aquaponic methods used in the Hanging Gardens of Babylon or the Chinampas of the Aztecs, these early techniques indicate mankind's long-standing fascination with leveraging water for plant growth. Fast forward to more recent times, the field experienced a watershed moment in 1860 when German botanists Julius von Sachs and Wilhelm Knop formulated the first nutrient solution, laying the scientific foundation for hydroponics [4]. Advances in nutrient solutions allowed for precise control over plant nutrition, enabling more efficient and reliable cultivation. Modern hydroponic systems, such as the Nutrient Film Technique (NFT), aeroponics, and Deep Water Culture (DWC), have further streamlined the process by integrating pumps, timers, and reservoirs, making hydroponics scalable for both individual gardeners and large-scale commercial operations. Additionally, lighting technology has also evolved, with High-Pressure Sodium (HPS) and Light Emitting Diode (LED) lights providing sustainable and efficient alternatives to natural light, thereby facilitating indoor hydroponic farming independent of seasons [5].

1.2 Automation and Control Systems

Today's hydroponics incorporates a high level of automation, using computer-controlled systems to modulate environmental variables like light and temperature, while reducing manual labor and specialized horticultural knowledge. These modern setups are grounded in the core principles of hydroponics, including the mechanics of nutrient delivery and environmental control. Various types of systems like the Nutrient Film Technique (NFT), aeroponics, and Deep Water Culture (DWC) are designed to deliver essential nutrients to plant roots through water-based media. These systems' efficacy relies on nutrient solutions composed of essential macronutrients and micronutrients that can be finely tuned for optimal plant growth. Proper management of these solutions, accounting for the EC (Electrical Conductivity) and pH levels, ensures effective nutrient uptake [6]. The lighting and temperature are rigorously controlled to simulate ideal growing conditions, with advancements like LED technology providing energy-efficient and spectrum-specific lighting options [7]. Therefore, hydroponics presents a methodical and highly controllable alternative to traditional agriculture, with an increased focus on optimization and efficiency.

1.3 Synergistic Technologies

The confluence of technological advancements in smart monitoring systems, Internet of Things (IoT) devices, and renewable energy sources has significantly enhanced the field of hydroponics, propelling it from a niche to a mainstream method of agriculture. Smart monitoring systems leverage advanced analytics algorithms and sensors to continuously measure variables like nutrient levels, pH balance, water temperature, and humidity, offering real-time data and actionable insights for optimal plant growth [8]. IoT contributes to this ecosystem by enabling seamless communication between devices, allowing, for example, nutrient pumps to communicate directly with monitoring systems. This level of connectivity also provides the

convenience of remote management, making it possible to control hydroponic setups from anywhere through smartphones or computers [9]. Adding to this are renewable energy sources such as solar panels and wind turbines, which provide a sustainable way to power the often energy-intensive hydroponic systems. These renewable energy solutions not only make these setups more sustainable but also reduce their overall carbon footprint [10]. Together, these technologies have a synergistic effect, creating a holistic environment that is not only optimal for plant growth but also convenient and sustainable for the growers.

1.4 Medium-Scale Applications

Commercial greenhouses that incorporate hydroponic systems are a transformative force in agriculture. These installations offer the distinct advantage of resource efficiency, especially concerning water usage. Given that water scarcity is an ever-growing concern, the conservation potential of hydroponic greenhouses is highly noteworthy. Coupled with the ability to precisely control climatic factors like temperature and humidity, these environments enable year-round crop production (Table 1), which is a significant advantage over traditional farming methods. However, these benefits come at a cost, both literally and figuratively. The initial financial investment required to set up a comprehensive hydroponic system in a commercial greenhouse can be quite high. The technical know-how needed to run these operations efficiently is often specialized, which poses a barrier to entry [11].

Table: 1 Most Suitable Plants for Hydroponic Cultivation and Their Recommended Techniques

Type	Common Name	Scientific Name	Cultivation Technique
Bulb Vegetables	Garlic	<i>Allium sativum</i>	Drip irrigation
	Onion	<i>Allium cepa</i>	NFT, Drip irrigation
	Leek	<i>Allium porrum</i>	NFT, Drip irrigation
Leafy Vegetables	Lettuce	<i>Lactuca sativa</i>	NFT, DWC
	Cabbage	<i>Brassica oleracea var. capitata</i>	NFT, DWC
	Brussels sprouts	<i>Brassica oleracea var. gemmifera</i>	NFT, DWC
	Mustard	<i>Brassica nigra</i>	NFT, DWC
	Spinach	<i>Spinaceaoleracea</i>	NFT, DWC
Root Vegetables	Beetroot	<i>Beta vulgaris</i>	Drip irrigation, aeroponics
	Turnip	<i>Brassica rapa</i>	NFT
	Radish	<i>Raphanus sativus</i>	Drip irrigation, aeroponics
Fruit Vegetables	Zucchini	<i>Cucurbita pepo</i>	Drip irrigation, NFT
	Cucumber	<i>Cucumis sativus</i>	Drip irrigation, NFT
Pulse Vegetables	Pea	<i>Pisum sativum</i>	Drip irrigation
	Bean	<i>Viciafaba</i>	Drip irrigation

Note: NFT stands for Nutrient Film Technique and DWC for Deep Water Culture.

Switching our focus to urban landscapes, hydroponic farming brings an array of solutions to the limitations of traditional agriculture. In cities where space is a luxury, hydroponics shines by enabling vertical farming. This approach allows for a higher yield per square foot, a boon in land-scarce urban settings. Moreover, producing food within the city reduces both transportation costs and the carbon footprint associated with bringing produce to market. However, like all systems, urban hydroponics is not without its challenges. Regulatory hurdles are a significant concern. Zoning laws often don't account for agricultural activities in urban settings, which can complicate the establishment of hydroponic farms. Additionally, the energy consumption associated with maintaining the environmental controls and lighting in an urban hydroponic system can be a substantial operational expense [12]. Integrating real-world examples brings life to the theoretical framework surrounding medium-scale hydroponics. Gotham Greens, based in New York, is a prime example of hydroponics finding a foothold in an urban setting. This company has successfully implemented a commercial hydroponic operation on a Brooklyn rooftop, but not without hurdles. They faced zoning restrictions and had to navigate the complexities of urban regulations, which included a significant amount of lobbying to get their project off the ground [13]. On the other side of the Atlantic, the Eden Project in the United Kingdom provides another fascinating case study. While its primary function is not purely commercial, it houses a vast hydroponic greenhouse and has a focus on education and research. The project required significant upfront costs and has had to rely on additional funding methods like grants and donations for sustainability [14].

1.5 Small-Scale Applications

Small-scale hydroponic systems have become increasingly popular in recent years for a variety of reasons. These systems can be as small as a single plant in a home setup or as expansive as a community garden serving dozens of families. The appeal lies in the system's inherent sustainability, resource efficiency, and the possibility of circumventing some of the limitations of traditional soil-based growing methods. This article will explore home-based systems, community gardens, and educational programs that make use of hydroponics, shedding light on the unique aspects and benefits of small-scale applications. Home-based hydroponic systems offer convenience and are incredibly accessible to even those with limited gardening experience. The simplicity of these setups is their most prominent feature. You don't need extensive farming expertise or even a large yard. Many people use countertop systems or dedicate a corner of a room to grow herbs, leafy greens, or small fruiting plants like cherry tomatoes. While the upfront cost can vary, affordable options are available. Moreover, ongoing maintenance costs for nutrients, electricity, and water are generally low, especially when compared to traditional gardening methods. These systems are exceptionally efficient in water usage, using up to 90% less water than soil-based gardens [15]. Home-based hydroponic systems aren't without their challenges. Understanding the basics of plant nutrient requirements and pH levels is essential, and initial setup can be intimidating for those new to the practice. There is also the issue of electricity usage, especially in larger setups or where high-intensity lights are used. The

operational expense, therefore, is not solely in the initial setup but in its day-to-day running as well. Community gardens using hydroponic systems offer a different set of advantages and challenges. These gardens often serve as a local source of fresh produce and are sometimes incorporated into community-supported agriculture (CSA) programs. They offer not just fresh food but also a hub for community interaction and education. However, these gardens often face hurdles, notably in securing the initial investment and in establishing a system of ongoing care and maintenance. Volunteer turnover and the complexity of hydroponic systems can lead to neglected gardens if not properly managed. Nevertheless, the benefits in terms of food security and community engagement often outweigh the drawbacks [16]. Another area where small-scale hydroponics has proven its mettle is in educational programs. Schools and educational institutions are increasingly adopting hydroponic systems as teaching tools. Not only do these systems serve to educate students about plant biology and agriculture, but they also offer hands-on STEM learning experiences. The benefits are myriad, ranging from instilling an appreciation for sustainability to imparting practical skills in agriculture and botany. Educational programs often collaborate with local businesses or non-profit organizations for the supply of equipment and technical expertise, creating a synergy between education and community [17]. The Eden Project in the United Kingdom offers a comprehensive example that encapsulates many aspects of small-scale hydroponic applications. Though not its primary function, the project's educational component is significant, offering insights into hydroponics and sustainable agriculture. Their hydroponic setups are small scale but demonstrate various methods and technologies, providing a learning experience for both students and visitors. As with other community and educational projects, funding and ongoing operational support are challenges [18].

1.6 Regulatory and Environmental Concerns

Laws and regulations form a vital framework for the growth and operation of hydroponic systems. The legal landscape affecting hydroponics varies from jurisdiction to jurisdiction, but there are some common threads. One primary concern is the classification of hydroponically grown produce in the context of organic certification. Traditional soil-based organic farmers have raised questions about whether hydroponically grown produce should be certified as organic, given that it doesn't cultivate soil—a cornerstone of organic agriculture. Regulatory bodies in different parts of the world have taken divergent stances on this issue. For example, in the United States, hydroponically grown produce can be certified as organic, whereas in the European Union, the standard requires soil as a medium for organic certification [19]. Another set of regulations concerns the use of agricultural chemicals in hydroponic systems. Given the closed-loop nature of many hydroponic setups, the introduction of pesticides or fungicides can have long-lasting effects and may even render the system inoperative. Farmers must adhere to approved lists of chemicals for use in hydroponic farming, ensuring both the safety of the produce and the integrity of the hydroponic system itself. However, these regulations can be burdensome for small-scale operators who may not have the resources to navigate the complex regulatory landscape.

Moving on to the environmental impact of hydroponic systems, water usage is often cited as one of its significant advantages over traditional agriculture. Traditional field farming techniques can be incredibly water-inefficient, losing a substantial amount of water to evaporation and runoff. In contrast, hydroponic systems are often "closed-loop," meaning that water is recirculated within the system, resulting in water use efficiencies up to 90% higher than traditional agriculture [20]. However, it's essential to note that this advantage can be offset if the hydroponic system isn't managed correctly. If there is a leak in the system or if water quality isn't adequately monitored, water usage can become inefficient, negating one of hydroponics' primary benefits. Energy usage in hydroponic systems is a topic of environmental concern, particularly when it comes to indoor hydroponic setups. These systems often require artificial lighting, temperature control, and air circulation, all of which consume electricity. While LED technology has made indoor lighting more energy-efficient, the energy requirement is still significant. When the electricity used for such operations is generated from non-renewable resources like fossil fuels, the environmental footprint of a hydroponic system can increase substantially. Some operations are turning to renewable energy sources to mitigate this issue. For example, solar and wind power are increasingly being used to offset the electricity demands of hydroponic farms [21]. The dual role of hydroponics as both a potential solution and a challenge in the context of sustainability is a subject of ongoing debate and research. While hydroponics can be a more resource-efficient method of food production, its environmental advantages are contingent on sustainable management practices and supportive regulatory frameworks. As hydroponic methods continue to evolve, so too will the laws and regulations that govern them. It will be crucial to align these regulations with the goal of making agriculture more sustainable while considering the unique attributes and challenges of hydroponic systems [22].

1.7 Economic Feasibility

Economic feasibility remains a pivotal aspect in the widespread adoption and scaling of any technology, and hydroponics is no exception. When examining the economic viability of hydroponic systems, key factors include initial setup cost, ongoing maintenance expenses, and return on investment (ROI) calculations, particularly for medium and small-scale setups. An understanding of these parameters is essential for stakeholders to evaluate the financial risks and rewards associated with hydroponic farming ventures. The initial setup cost of hydroponic systems can vary widely based on the scale and complexity of the operation. Medium to large-scale commercial ventures necessitate significant investments in infrastructure, including high-quality hydroponic systems, climate control solutions, and sometimes, even artificial lighting setups. These costs can run into hundreds of thousands of dollars, sometimes even more. Meanwhile, small-scale setups for home and educational use may only require a few hundred dollars. The affordability of smaller systems has democratized access to hydroponics, making it an appealing option for those with limited space and financial resources. Nonetheless, regardless of scale, these upfront costs pose a financial barrier that can deter potential entrants from embracing hydroponic methods [23]. Ongoing maintenance expenses represent another crucial

economic variable. Hydroponic systems are not "set it and forget it" operations. They require a consistent investment of time and resources to ensure optimal plant growth and system functionality. The cost of electricity, water, and nutrient solutions can accumulate quickly, especially for larger systems. The system requires periodic checks for pH levels, nutrient concentrations, and any potential for the spread of disease or pests. Larger operations may also need to hire labor for tasks like plant pruning, harvesting, and system maintenance, thereby increasing the operational expenses. ROI calculations offer a more comprehensive picture of the economic feasibility by linking the costs and the revenues. For medium-scale setups, such as commercial greenhouses, the high initial costs could potentially be offset by substantial yields and the possibility of year-round farming, thanks to controlled environmental conditions. Many commercial operations aim for premium markets, such as organic produce or specialty crops, to command higher prices that can justify the initial investment [24]. On the other hand, small-scale hydroponic systems for home or educational use may not aim for a financial ROI, but rather focus on educational value, the joy of home gardening, or community-building benefits. In these cases, the concept of "return" extends beyond monetary gains to include other forms of value such as learning, leisure, or enhanced quality of life.

Assessing the ROI for hydroponic systems is often more complex than it appears. While yield per square foot is generally higher than traditional soil-based farming, the costs are also significantly higher. One needs to factor in the cost of electricity, especially if artificial lights are used, the cost of water purification, and the ongoing costs of nutrients and growing media. These variables can significantly impact ROI, sometimes leading to a longer period for breaking even than initially expected [25]. Economic feasibility is therefore not a static or monolithic factor; it is a dynamic variable influenced by a multitude of factors ranging from the scale of operation to the specific crops being grown, local electricity and labor costs, and market demand for the produce. As hydroponic technology continues to advance and become more cost-effective, and as more data on successful hydroponic business models become available, it will become increasingly feasible to make accurate economic projections for different types of hydroponic farming setups [26].

2.0 FUTURE PROSPECTS

The concept of hydroponics, though not entirely novel, has never been as consequential as it is in today's era of burgeoning population and diminishing natural resources. While hydroponics has made notable strides in both technological finesse and popular acceptance, the future of this agricultural method hinges on numerous variables. Of paramount importance are the forthcoming technologies set to revolutionize the hydroponic landscape and the potential for these systems to scale effectively for mainstream adoption. Upcoming technologies in hydroponics are steering the field toward an era where automation, artificial intelligence, and even nanotechnology could become integral components of these soil-less farming systems. One can think of nutrient delivery, for instance. Traditionally, nutrients are manually added to water reservoirs and require frequent checks to ensure correct pH and nutrient levels. Emerging technologies are automating

this process, making use of sensors to monitor nutrient levels and adjusting them in real-time. These intelligent systems can considerably decrease the margin for human error, thereby increasing yield and resource efficiency. Additionally, water usage, a significant concern in traditional agriculture, can be optimized more efficiently through smart monitoring systems [27, 32]. Yet, even more revolutionary is the development and impending application of nanotechnology in hydroponics. Researchers are working on nanoparticle-based solutions for more efficient nutrient delivery to plants. By engineering the size and shape of these nanoparticles, scientists aim to develop a system where plants can absorb nutrients more effectively, thus reducing the need for excess fertilization. Such technology not only cuts down on the cost of nutrients but also has the potential to diminish nutrient runoff, a serious environmental concern associated with both traditional and hydroponic agriculture. The integration of IoT (Internet of Things) in hydroponic farming is another game-changer. Sensors can provide real-time information on various parameters such as light, temperature, and humidity, allowing growers to adjust conditions instantaneously for optimal plant growth. Coupled with machine learning algorithms, these smart systems can autonomously adapt and make decisions, thereby minimizing human intervention while maximizing productivity. This IoT-enabled 'smart farming' could usher hydroponics into an era of unprecedented efficiency and sustainability.

Technology is but a tool; its impact is most palpable when scaled effectively. Here lies another pivotal aspect of hydroponics' future: the potential for scalability and mainstream adoption. With burgeoning global populations and urbanization, the demand for scalable food production systems is higher than ever. Hydroponics is well-suited for urban environments, where space is at a premium and traditional farming is not viable. Moreover, the modular nature of hydroponic systems allows for incremental expansion, thereby providing a scalable solution adaptable to varying demands [28]. Several initiatives around the globe already demonstrate successful scaling of hydroponic operations. Case studies in various countries illustrate how entrepreneurs are converting warehouses and even multi-story buildings into hydroponic farms, supplying local markets with fresh produce year-round. These endeavors, though still isolated, provide a template for what large-scale hydroponic farming could look like. They also serve as a proof of concept, demonstrating that hydroponics can indeed be scaled to meet the demands of a larger population [29, 34].

3.0 RECOMMENDATIONS

Recommendations on the implementation and future research on hydroponic systems are essential for shaping the trajectory of this burgeoning field. As the technology evolves and becomes increasingly complex, the need for a well-defined research agenda and actionable advice for medium or small-scale applications becomes more apparent. This paper aims to provide both academic and practical insights to guide the future direction of hydroponics. First and foremost, there's a pressing need for more research on optimizing nutrient solutions. Currently, a lot of the nutrient mixtures used in hydroponics are borrowed from traditional

agriculture, with little regard for the unique attributes of soil-less farming. Tailoring nutrients to specific crops in hydroponic settings could lead to greater resource efficiency, as well as higher yields. Research in this area would not only have academic merit but would also be immediately actionable, benefiting both medium and small-scale setups [30, 33]. Another vital area requiring further study is the environmental footprint of hydroponic systems. Although hydroponics is often touted as a sustainable alternative to traditional farming, there's a lack of comprehensive lifecycle analyses to confirm this. Research comparing the total water, energy, and carbon footprints of hydroponic systems against those of soil-based systems could provide valuable insights into the true sustainability of this farming method. A thorough understanding of its environmental impact will be crucial as hydroponic systems continue to scale and become more prevalent [31]. On the technology front, given the rapid advancements in machine learning and artificial intelligence, a focus on how these technologies can integrate into hydroponic systems for better predictive modeling and automated decision-making is warranted. These smart systems could be invaluable in large-scale commercial operations where managing multiple variables manually would be challenging and resource-intensive. However, their applications aren't restricted to large setups. Small and medium enterprises would also greatly benefit from automated systems that simplify the monitoring and maintenance of hydroponic farms[35].

4.0 CONCLUSION

In the rapidly evolving landscape of agriculture, hydroponics has emerged as a revolutionary method, incorporating advancements in automation, monitoring, and sustainability. While the core principles of hydroponics remain anchored in soilless cultivation, a slew of modern technologies like smart sensors, IoT devices, and renewable energy sources have converged to redefine the parameters of what is possible in this field. From ancient civilizations to state-of-the-art setups, hydroponics has undergone a transformation, becoming more accessible and efficient. These enhancements promise a future where hydroponic farming is not just an alternative but a mainstream, sustainable solution for both commercial and domestic growers. Thus, hydroponics stands as a testament to the power of innovation to reshape traditional practices, offering new avenues for food production in an increasingly resource-constrained world.

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