

Exploring hydroponics and the associated technologies for use in medium-and small-scale operations- A review

Abstract

Hydroponics, the science of soilless agriculture, has emerged as a pivotal paradigm in modern cultivation practices, addressing myriad challenges of traditional farming and offering avenues for high-efficiency, sustainable food production. This review delves into the anticipated future directions of hydroponics, capturing its interdisciplinary evolution. Central to this trajectory is the integration of Artificial Intelligence (AI) and machine learning, aiming to augment precision in every facet of hydroponic cultivation, from nutrient balance to disease prediction. Complementing technological advancements is the burgeoning realm of genomics, poised to craft crop varieties intrinsically optimized for hydroponic conditions, promising both enhanced yields and improved nutritional profiles. Sustainability remains an unwavering focus, with innovative methodologies underscoring recycling and resource optimization, ensuring minimal waste and maximal output. The synergistic amalgamation of hydroponics with other agricultural models, notably aquaponics, paints a picture of integrated, multi-tiered ecosystems that not only boost productivity but also bolster ecological resilience. Such integrations herald a future where farming transcends singular methodologies, evolving into harmonized systems that capitalize on the strengths of individual disciplines. In essence, the horizon of hydroponics is not one of mere technical advancement but represents a holistic evolution, seamlessly melding technology, biology, and ecology. This review aims to provide a comprehensive overview of these trajectories, offering insights into the potentialities and promises that the future of hydroponics holds.

Keywords: *Hydroponics, Genomics, Sustainability, Aquaponics, Technology*

Introduction

Hydroponics, derived from the Greek words "hydro" (water) and "ponos" (work), is a method of cultivating plants using nutrient-rich water solutions without the need for soil. This technique has gradually cemented its position in the agricultural lexicon, promising an innovative approach to resource management and crop production, especially in environments where traditional farming encounters challenges. Hydroponics can be defined as a soilless cultivation method wherein plants are grown in an aqueous solution containing all the essential nutrients required for their growth [1]. In such a system, the roots of the plants are either suspended in water or supported by an inert medium like perlite, vermiculite, or rock wool. The primary objective of hydroponics is to deliver water and nutrients directly to the plant roots in the right proportions, ensuring optimal growth conditions. The origins of hydroponics can be traced back to ancient civilizations, suggesting that this is not a new phenomenon but rather a rediscovered and refined agricultural practice. The famous Hanging Gardens of Babylon, one of the Seven Wonders of the Ancient World, is believed by some historians to have used a form of hydroponics. These terraced gardens, as described by Philo of Byzantium in the 4th century B.C., employed an intricate irrigation system that could potentially be categorized as an early hydroponic setup [2]. Similarly, the floating gardens or 'Chinampas' of the Aztecs in ancient Mexico can be seen as another early form of

hydroponics. The Aztecs constructed artificial islands on lakebeds, where they cultivated a variety of crops. These islands, made from the lake's silt and decaying vegetation, were highly fertile and had an abundant supply of water, resembling many contemporary hydroponic setups [3]. In more recent history, hydroponics gained scientific interest in the 17th century when researchers began to identify the essential nutrients plants required and discovered that soil acted merely as a nutrient reservoir. By the 19th and early 20th centuries, scientists, including the German botanist Julius von Sachs and American plant physiologist Dr. William Frederick Gericke, made significant advancements in plant nutrition and hydroponic techniques [4]. Dr. Gericke, in particular, is credited with popularizing hydroponics in the modern era. In the 1930s, he demonstrated that it was possible to cultivate plants in a soilless nutrient solution on a large scale. His successful experiments showcased tomato plants grown to an astonishing height, garnering significant media attention and subsequently propelling hydroponics to the forefront of agricultural research [5].

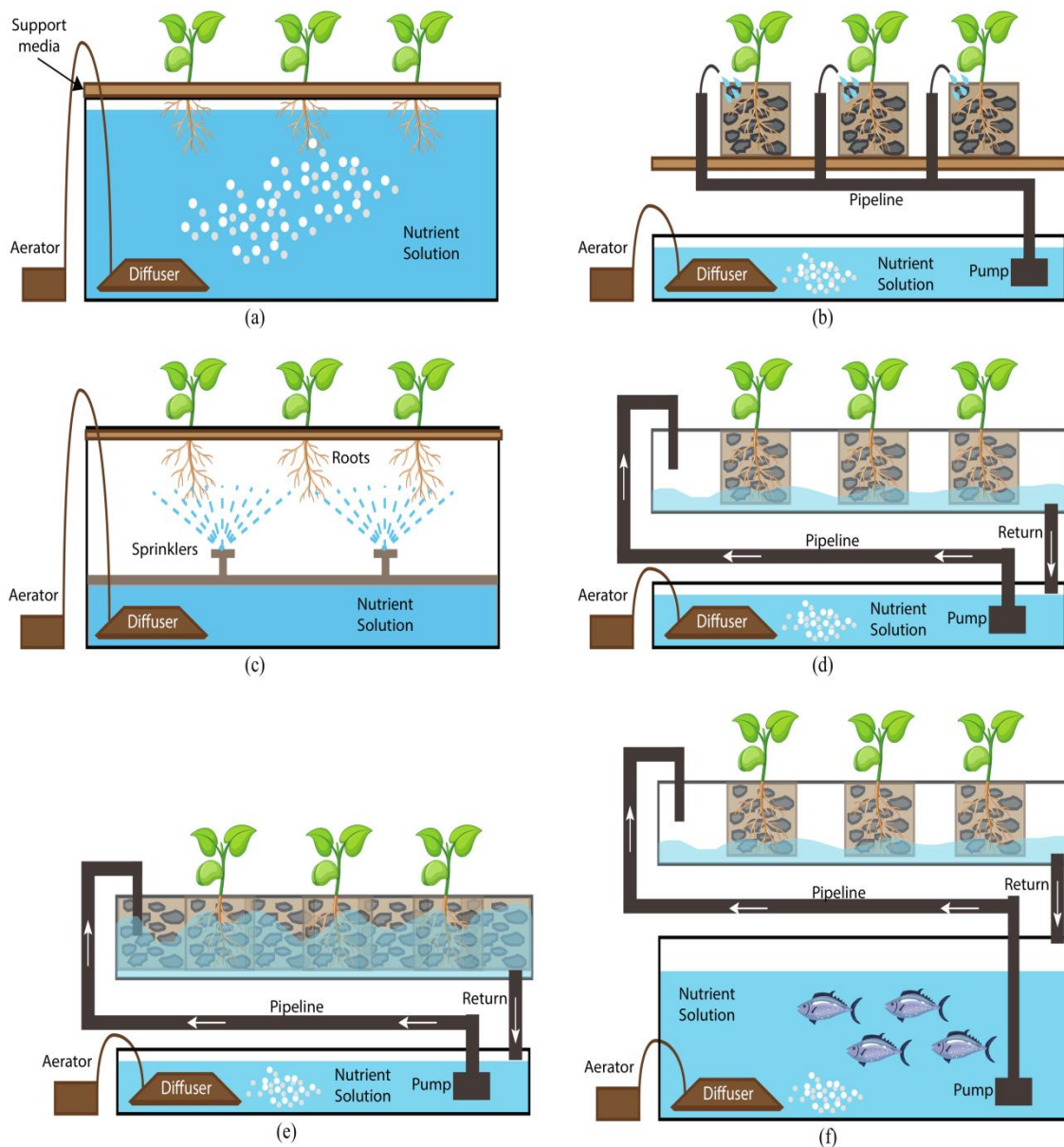


Figure 1. Different types of hydroponic systems. (a) Deep Water Culture. (b) Drip System. (c) Aeroponics. (d) Nutrien Film Technique (NFT). (e) Ebb and flow. (f) Aquaponics.

Importance of Hydroponics in the Modern Agricultural Scenario

Today's global agricultural landscape is grappling with numerous challenges. With the burgeoning human population, there is increasing pressure on agricultural systems to produce more food, often with limited resources. The World Bank predicts that by 2050, food production will need to increase by 50% to feed the estimated 9 billion people [6]. Coupled with issues like soil degradation, water scarcity, urbanization, and the unpredictable nature of climate change, there's an imperative need for innovative, sustainable farming practices. This is where hydroponics shines. Hydroponic systems, by eliminating the need for soil, directly address the challenges of soil degradation and erosion. They typically use significantly less water than traditional farming – up to 90% less, in fact [7]. Such water efficiency is paramount in regions suffering from water scarcity. Additionally, the controlled nature of hydroponics allows for year-round cultivation, irrespective of external climatic conditions. This ensures a constant supply of fresh produce, making it especially valuable for urban areas where importing food can be both costly and environmentally taxing. Another significant advantage is the potential for vertical farming. Since hydroponic systems can be stacked, they can be incorporated into urban architectures, turning multi-storied buildings into productive farms. Such practices not only reduce the carbon footprint associated with transporting food over long distances but also help in reconnecting urban populations with their food sources.

Table 1. Most Suitable Plants to Grow by Hydroponics [8]

Type	Common Name	Scientific Name	Cultivation Technique
Bulb Vegetables	Garlic	Allium sativum	Drip irrigation
	Onion	Allium cepa	NFT, Drip irrigation
	Pore	Allium porrum	NFT, Drip irrigation
Leafy Vegetables	Lettuce	Lactuca sativa	NFT, DWC
	Cabbage	Brassica oleracea var. capitata	NFT, DWC
	Brussels sprouts	Brassica oleracea var. gemmifera	NFT, DWC
	Mustard	Brassica nigra	NFT, DWC
	Spinach	Spinaceaoleracea	NFT, DWC
	Chard	Beta vulgaris var. cicla	NFT, DWC
	Water cress	Nasturtium officinale	NFT, DWC
	Celery	Apium graveolens	NFT, DWC
	Parsley	Petroselinum crispum	NFT, DWC

	Coriander	Coriandrum sativum	NFT, DWC, Drip irrigation
	Purslane	Portulaca oleracea	NFT, DWC
Root Vegetables	Beetroot	Beta vulgaris	Drip irrigation, Aeroponics
	Jicama	Pachyrrhizuserosus	Drip irrigation
	Turnip	Brassica rapa	NFT
	Radish	Raphanus sativus	Drip irrigation, Aeroponics
	Yucca	Manihot esculenta	NFT, Drip irrigation
	Carrot	Daucus carota	Drip irrigation, Aeroponics
Tuber Vegetables	Sweet potato	Ipomoea batatas	Drip irrigation
	Potato	Solanum tuberosum	Drip irrigation
Stem Vegetables	Swede	Brassica oleracea var. gongyloides	Drip irrigation
	Asparagus	Asparagus officinalis	NFT, DWC
Inflorescent Vegetables	Artichoke	Cynara scolymus	Drip irrigation
	Broccoli	Brassica oleracea var. Italica	Drip irrigation, NFT
	Cauliflower	Brassica oleracea var. botrytis	Drip irrigation, NFT
	Huauzontle	Chenopodium sp.	NFT, DWC
Fruit Vegetables	Zucchini	Cucurbita pepo	Drip irrigation, NFT
	Cucumber	Cucumis sativus	Drip irrigation, NFT
	Cantaloupe	Cucumis melo	Drip irrigation, NFT
	Watermelon	Citrullus vulgaris	Drip irrigation
	Green bean	Phaseolus vulgaris	Drip irrigation
	Squash	Sechiumedule	Drip irrigation
	Chile	Capsicum annuum	Drip irrigation
	Eggplant	Solanum melongena	Drip irrigation
	Tomato	Solanum lycopersicum	Drip irrigation, NFT
	Tomato	Physalis ixocarpa	Drip irrigation, NFT

Pulse Vegetables	Pea	Pisum sativum	Drip irrigation
	Bean	Vicia faba	Drip irrigation
	Sweet Corn	Zea mays	Drip irrigation

NFT: Nutrient Film Technique

DWC: Deep Water Culture

Advantages of Hydroponics

Hydroponics, the science and art of soilless cultivation, has become the subject of growing intrigue, especially in the backdrop of an expanding global population, dwindling arable land, and increasing water scarcity. While the method isn't entirely new traces of its principles date back to ancient civilizations like the Babylonian its contemporary relevance is more pronounced than ever. Whether we consider the desire to produce more using less or the intent to bypass some of the inherent challenges of traditional agriculture, hydroponics offers tangible solutions. Delving deeper into its benefits, we uncover aspects like water efficiency, precision in nutrient delivery, and its intrinsic flexibility in scalability and location, among others.

Water Efficiency

Water, the lifeblood of agriculture, remains a depleting resource. In numerous regions across the globe, especially arid zones and growing urban centers, the availability of water for agriculture is a pressing concern. Traditional agriculture, where water is often applied liberally to vast fields, frequently results in wastage through run-off, evaporation, or inefficient absorption. Hydroponics, on the other hand, emerges as an advocate of water conservation [9]. In hydroponic systems, the approach to water is cyclical. Water containing dissolved nutrients is delivered directly to plant roots. The unused water, instead of being lost, is recirculated in the system. Such systems can report up to 90% less water usage compared to their soil-based counterparts. In effect, hydroponics doesn't just save water; it maximizes its use, ensuring that each drop plays a role in plant growth.

Control over Nutrient Delivery

Every seasoned farmer understands the unpredictable nature of soil. Variabilities in soil composition can make nutrient delivery inconsistent, leading to either deficiencies or toxicities. Hydroponics turns this narrative around. Instead of relying on the vagaries of soil to feed plants, hydroponics empowers growers with the ability to create custom nutrient solutions tailored to the precise needs of the plants being cultivated [10]. Such meticulous control over nutrients means plants no longer face deficiencies, ensuring they always have what they need for optimal growth. It also results in less nutrient wastage, as only the required amounts are mixed into the water. This not only has implications for crop health but also for the environment. Traditional farming, with its propensity for over-fertilization, often sees nutrient runoff that can contaminate local waterways. The precision of hydroponics eliminates such possibilities.

Reduced Soil-Related Diseases

Soil, despite being the natural medium for plant growth, harbors its set of challenges. A myriad of pathogens, from fungi to bacteria, finds solace in soil, often causing diseases that can decimate entire crops. The transition to hydroponics moves away from this problem, offering a solution that can substantially reduce, if not eliminate, the threat of soil-borne diseases [11]. While no cultivation method can claim complete immunity from diseases, the sterile or controlled environment of hydroponic systems means that many pathogens find it challenging to establish themselves. The result is healthier plants that require fewer chemical interventions, leading to cleaner produce and reduced costs for growers.

Flexibility in Location and Scalability

Traditional farming remains bound by the whims of nature. Factors such as soil quality, rainfall, temperature, and altitude can dictate what can be grown and when. Hydroponics, in its essence, offers a liberation from these constraints. As it doesn't require soil and typically operates in controlled environments like greenhouses, it can be practiced virtually anywhere [12]. This flexibility extends to scalability. From sprawling commercial farms to a compact setup in an urban apartment, hydroponics can be adapted to fit various scales. This modularity means that food production can be brought closer to consumption centers, reducing the carbon footprint associated with transportation and offering fresher produce to consumers.

Enhanced Growth Rates and Yields

All the advantages mentioned converge towards one central benefit: productivity. With optimal conditions — perfect nutrient levels, fewer diseases, and consistent water supply — plants in hydroponic systems often outperform their soil-grown counterparts. Research indicates that certain hydroponically grown crops can mature faster by up to 25% and yield more by up to 30% [13]. For a world facing the daunting challenge of feeding an ever-increasing population, such efficiency gains are invaluable. It translates to more food produced in less time, using fewer resources.

Hydroponic Systems

The realm of agriculture is not only ripe with traditional methodologies but has in recent decades also been invigorated by innovative technologies. One such marvel is hydroponics, an age-old concept that has been modernized with scientific insights and technological advancements. Central to hydroponics are the distinct systems or methods that facilitate soilless plant cultivation. Each of these systems serves the fundamental purpose of delivering water and nutrients to the plants, yet they do so using unique mechanisms tailored to specific needs and environments. The Nutrient Film Technique (NFT) is a quintessential hydroponic system that has garnered popularity for its simplicity and efficiency. The essence of NFT lies in its name; a thin film or layer of nutrient-rich water is continually flowed across the roots of the plants, which are supported by sloping troughs or channels. This ensures that the plant roots remain in contact with both the nutrient solution and air, creating an optimal environment for growth. The lack of growing medium in NFT systems means that there's a delicate balance to maintain. While the constant flow of nutrients ensures that plants receive all the necessary elements for growth, the absence of any buffer means that power outages or pump failures can quickly lead to plant stress or death [14]. Contrastingly, Deep Water Culture

(DWC) offers a different approach to hydroponic cultivation. In this system, plants are suspended, with their roots immersed in a nutrient solution. The key to DWC's efficacy lies in oxygenating this solution, ensuring that the submerged roots receive ample oxygen for respiration. This is typically achieved using air stones or diffusers, akin to those seen in aquariums. DWC systems stand out for their simplicity and low maintenance. Moreover, the consistent access to water, oxygen, and nutrients often translates into rapid plant growth [15]. While the Wick System might sound primitive, its elegance lies in its simplicity. At its core, the Wick System employs wicks, often made of absorbent materials like cotton, to draw nutrient-rich water from a reservoir to the plants' root zone. This capillary action ensures a steady supply of water and nutrients to the plants. Given its passive nature, without the need for pumps or electricity, the Wick System is especially favored for smaller setups or beginner hydroponic enthusiasts. Drip Systems, on the other hand, echo the sophistication one might associate with modern hydroponics. As the name suggests, these systems deliver water and nutrients to plants via a network of tubes, pipes, and drippers. By controlling the rate and frequency of the drips, growers can meticulously regulate the nutrition each plant receives. While the system offers precision, it also demands careful monitoring and maintenance to prevent clogging and ensure uniform distribution of nutrients [16]. The future-forward nature of hydroponics is perhaps best exemplified by Aeroponic Systems. In aeroponics, plant roots dangle in the air and are intermittently misted with a nutrient solution. The exposure to air ensures high oxygenation, while the misting provides essential hydration and nutrition. NASA's interest in aeroponics for space cultivation underscores the system's potential. However, the fine balance required, especially concerning misting frequency and nozzle maintenance, means that aeroponics often demands more attention and care from the grower [17].

Table 2. Main Substrates Used in Hydroponics [18]

Material	Advantages	Disadvantages
Sand	Economically viable, good porosity features, and provides good plant support	High density (around of 1500 kg/m ³), low retention of water, susceptible to salt accumulation
Perlite	Low density (around of 90 kg/m ³), biologically inert, neutral pH, highly available	Expensive, low water retention capacity
Vermiculite	Low density (around 80 kg/m ³), high nutrient holding ability, good water holding ability	Expensive, energy consuming product
Rockwool	Low density (around 80 kg/m ³), ease of handling, totally inert, sterile from pathogens, eases nutrition management in plants	Negative impacts on human health when is reused
Coconut coir	Low density (around 60 kg/m ³), good air content and water holding capacity, pH in ranges of 5–8	High salt level content, energy consumption during transport

Peat/Peat moss	Inert, high water storage capacity, prevents leaching of nutrients	Negative environmental impacts such as loss of soil organic carbon, relatively expensive
Pumice	Cheap and long-lasting usage, chemically inert, low density	Particle size and hydraulic properties affect the growth and yield of crops

Key Technologies Associated with Hydroponics

Hydroponics, while rooted in an age-old concept of soilless cultivation, has surged to the forefront of agricultural innovation. The dramatic transformation from rudimentary soilless cultivation techniques to sophisticated hydroponic farms, teeming with technology, signals the profound influence of modern technological advancements on this farming method. As we navigate the technological terrain of hydroponics, we encounter a suite of technologies that not only augment hydroponic systems but also redefine the very essence of contemporary farming. LED Lighting and Spectrum Control stand as cornerstones in the edifice of hydroponic technologies. The importance of light in plant growth is unquestionable, but hydroponics takes this understanding a step further by harnessing LED technology. Unlike traditional lighting systems, LED lights offer the unique advantage of spectrum control. Plants, during their lifecycle, require different light spectra; for instance, blue light can promote vegetative growth, while red light often stimulates flowering. The ability to modulate light spectra using LEDs allows hydroponic farmers to cater to these specific needs, optimizing growth rates and ensuring bountiful yields. LEDs, known for their energy efficiency, align with the sustainability ethos of hydroponic farming [19]. Yet, light is just one facet of the intricate hydroponic environment. Automated Nutrient Delivery Systems underscore the essence of precision farming, a hallmark of hydroponics. The vitality of plants in a hydroponic setup hinges on the consistent and balanced delivery of nutrients. Automated systems, equipped with sensors, ensure that plants receive optimal nutrition by continually monitoring nutrient concentrations and adjusting them based on real-time feedback. This eliminates the pitfalls of over or under-fertilization, steering clear of nutrient burn or deficiency, and facilitating healthier plant growth [20]. The sophisticated nexus of sensors extends beyond just nutrient delivery. Remote Sensing and Monitoring introduce a dimension of convenience and precision to hydroponic farming. With sensors strategically embedded within the hydroponic setup, growers can monitor parameters like pH, temperature, humidity, nutrient levels, and more, often from remote locations. This constant surveillance ensures that any discrepancies or anomalies are promptly detected and rectified, minimizing risks and ensuring a stable growing environment.

Challenges in Hydroponics

While hydroponics has long been heralded as the vanguard of modern agricultural practices, offering innovative solutions to traditional farming woes, it is not without its challenges. As is the case with any revolutionary approach, hydroponics presents a set of unique problems that growers must navigate. These challenges range from economic constraints to technical intricacies, each demanding understanding and mitigation for the successful application of hydroponic methods. One of the most formidable barriers facing potential hydroponic growers

is the Initial Setup Cost. The transition from soil-based cultivation to a hydroponic system often requires a substantial financial outlay. Unlike traditional farming, which primarily demands soil preparation and basic infrastructure, establishing a hydroponic farm necessitates the procurement of specialized equipment like growth chambers, lighting systems, nutrient delivery mechanisms, and monitoring devices. The need for quality materials, such as food-grade reservoirs and non-toxic tubing, can further inflate costs. While these investments are typically recouped over time due to higher yields and faster growth cycles in hydroponics, the initial financial burden can be a deterrent for many, especially small-scale farmers and hobbyists [21]. The complexities of hydroponics don't end with setup. The system's intricate nature means that its operation demands not only labor but Skilled Labor and Knowledge. Soilless cultivation pivots on precision. Factors like pH levels, nutrient concentration, and light exposure must be meticulously managed. Such precision mandates a deep understanding of plant physiology, nutrient dynamics, and system mechanics. Hence, hydroponic growers often need training or specialized knowledge to operate their farms efficiently. This requirement can exacerbate challenges, especially in regions where access to training is limited or where hydroponic know-how is nascent [22]. Alongside knowledge constraints, hydroponic farmers must grapple with the intricacies of Water and Nutrient Solutions. Water, the lifeblood of hydroponic systems, must meet stringent quality standards. The presence of contaminants or unfavorable pH levels can significantly hamper plant growth. Similarly, nutrient solutions, which replace soil as the primary source of plant nutrition, must be meticulously balanced. An imbalance or deficiency in essential minerals can lead to stunted growth, leaf discolorations, or reduced yields. While hydroponic systems offer the advantage of nutrient control, this control becomes a double-edged sword, with the onus of maintaining perfect balance resting on the grower's shoulders.

Hydroponics in Medium-and Small-Scale Operations

Hydroponics, a farming method once perceived as the exclusive domain of large-scale commercial growers and futuristic agritech firms, has witnessed a remarkable transformation. It has seamlessly integrated itself into the fabric of medium and small-scale operations. The proliferation of hydroponics at these scales offers testimony to its versatility, adaptability, and the unique advantages it presents, especially in unconventional agricultural settings. When delving into the world of medium and small-scale hydroponics, questions regarding Viability and Profitability are paramount. The intricacies and nuances of hydroponics often lead to apprehensions about its feasibility at smaller scales [27]. While the initial investment, especially in specialized equipment and infrastructure, can be daunting, the returns on investment are compelling. The higher yields, faster growth cycles, and ability to cultivate off-season crops often mean that growers can achieve profitability in shorter time frames compared to conventional farming methods. Additionally, the reduced land requirement, coupled with the capability to stack vertically, allows small-scale hydroponic growers to maximize their output per square foot [28]. This spatial efficiency is especially invaluable in areas where land is a premium resource. The soilless nature of hydroponics also implies reduced costs related to soil tilling, pest control, and water usage, further accentuating its economic viability at smaller scales [23]. Narratives of success, as with any domain, hold profound persuasive power. Hydroponics is no exception. Across the globe, a tapestry of Case Studies showcases the triumphs of medium and small-scale hydroponic enterprises. Take, for instance, the story of a retired couple in Australia, who transformed their backyard into a

thriving hydroponic lettuce farm. Within a small greenhouse, they utilized a deep water culture system, harnessing the Australian sun and a meticulous nutrient regimen to produce premium lettuce varieties, which soon became a local delicacy. Their venture not only afforded them a sustainable income but also rejuvenated local interest in fresh, locally-sourced produce. Another tale emerges from the bustling streets of Bangkok, where a young entrepreneur converted the terrace of a residential building into a hydroponic haven, cultivating exotic herbs and vegetables that catered to the city's burgeoning gourmet restaurants. These stories, while diverse in their geographic and cultural contexts, share a common thread — the transformative power of hydroponics when wielded with innovation, diligence, and passion [24].

Future Directions

The field of hydroponics, which has already charted a transformative trajectory in the agricultural domain, stands on the cusp of even more groundbreaking innovations. The horizon of hydroponic cultivation promises not just incremental improvements but paradigm-shifting advancements that have the potential to redefine our relationship with food production. These developments, driven by a confluence of technology, biology, and environmental consciousness, underscore the dynamism and potential that hydroponics embodies. One of the most anticipated revolutions in hydroponics is the integration of advancements in AI and Machine Learning [25]. The essence of hydroponics lies in its precision — the meticulous balance of nutrients, the careful regulation of light cycles, and the optimal maintenance of pH levels. While human expertise has traditionally overseen these parameters, the advent of AI and machine learning holds the promise to elevate this precision to unparalleled heights. Algorithms, trained on vast datasets spanning diverse crops and environmental conditions, can predict optimal nutrient mixes, preempt potential diseases, and even adjust growth conditions in real-time in response to minute physiological changes in plants. This not only translates to improved yields and crop quality but also ensures resource optimization, minimizing waste. Machine learning models, with their capacity to discern patterns beyond human cognition, can also offer insights into crop rotations, pest control, and harvest predictions, refining the entire cultivation cycle [26].

Conclusion

The future of hydroponics represents a convergence of technology, biology, and environmental stewardship. With the infusion of AI and machine learning, precision in cultivation is set to achieve unprecedented levels, ensuring optimal yields and resource utilization. Complemented by genomic insights, crops will be tailored to harness the full potential of soilless farming. A renewed emphasis on recycling and sustainability underscores the holistic approach, seeking not just productivity but also ecological harmony. The integration of models like aquaponics exemplifies this harmonious vision, merging disciplines to create resilient, high-yield ecosystems. As hydroponics evolves, it promises a transformative impact on agriculture, melding innovation with sustainability, and steering the future of food production towards a more balanced and efficient horizon.

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