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REVIEW PAPER

An Overview of the Opportunities and Challenges of Hydroponic Smart Farming Ecosystem for Sustainable Crop Production

Mukesh Kumar[1*], Neetu Kataria[1], Rajeev Kumar[3], Rekha Jangra[2], Sajjan Kumar[3], Pardeep Kumar[3] and Vinod Kumar[3]

[1]Department of Botany, Government College Bahadurgarh, Jhajjar, India
[2]Department of Botany, Pt. Chiranji Lal Sharma Government College, Karnal, Haryana, India
[3]Department of Geography, Government College, Bahadurgarh, Jhajjar, Haryana, India

*Corresponding author: mukbot23@gmail.com (**ORCID ID:** 0009-0004-3362-5119)

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ABSTRACT

Hydroponic farming combined with smart technology is a new approach that shows potential for efficient and sustainable crop production. This method delivers nutrients directly to the roots of plants, doing away with the need for soil and saving water. In "smart farming," sensors, automation, and the Internet of Things (IoT) are employed to provide continuous monitoring of plant vitality, nutrient levels, and soil conditions, hence facilitating fine-grained control and optimization. The technology-driven approach increases crop yield, accelerates rates of growth, and maintains optimal conditions year-round, independent of weather or other environmental factors. Furthermore, smart farming encourages environmentally safe pest management techniques, reduces the amount of waste generated, and reduces the need for organic chemical inputs. This innovative approach could have a profound impact on the agriculture industry by promoting regionalized food production, improving food security, and incorporating more resilient farming techniques. This in-depth analysis explores current hydroponics trends while highlighting new developments in automated artificial intelligence (AI) systems, data acquisition, remote cultivation, and domotism. In addition, the paper highlights the many applications and benefits of hydroponic smart farming technology, highlighting the conditions that must be met to attain effectiveness in this cutting-edge field. It also looks at future objectives and possible breakthroughs, opening the door for more developments in hydroponic smart farming.

HIGHLIGHTS

- Hydroponic smart farming reduces water use by up to 90%, optimizes nutrient delivery, minimizes pesticide reliance, and supports year-round crop production with higher yields compared to conventional soil farming.
- Incorporation of IoT, AI, automation, and domotics enables precise monitoring of plant health, nutrient levels, and environmental conditions, enhancing productivity and resilience in controlled environments.

Keywords: Smart Farming, Hydroponics, IoT, Sensors, Domotics, Remote Cultivation

Meeting the world's food demands is one of the biggest issues of the twenty-first century, with estimates indicating that there will be 9.8 billion people on the planet by 2050 (Anbukkani P, 2016). According to current estimates, 70% more food must

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be produced overall than is now the case in order to feed this growing population (Asao T, 2012). The burgeoning population and climate change posing a challenge to meet the sufficient and quality food, fodder and fuel demand in 2050. The cultivable land is also shrinking due to industrialization and urbanization as the availability was 0.50 ha in 1960 which has come down at 0.25 ha (Gautam *et al.* 2021). The effects of climate change, and other environmental constraints limit the amount of land that can be cultivated to enhance agricultural output using existing methods. These interrelated issues put future global food security in jeopardy and highlight the need for creative solutions to increase crop yields in a sustainable way (Carmassi *et al.* 2005).

To overcome this problem, Hydroponic farming is one of the best alternatives. Soilless culture is a novel methodology for growing of crops or plants without soil by using growing media, which can be solid, liquid, organic or inorganic material. The term hydroponics was derived from the Greek word *Hydro* meaning Water and *ponos* meaning labour *i.e.* water work, which was coined by William Gericke, a professor in 1930s. Hydroponic farming is a technique of growing plants in nutrient-rich solution with or without the use of an inert medium like sand, gravel, rock wool, peat moss, sawdust Coconut fiber, vermiculite, perlite etc., to provide physical support to the plant (Anupriya *et al.* 2025). To encourage technology innovators and give farmers access to precision solutions, the public sector must be involved (Hussain *et al.* 2014). One of the major advantages of soilless media is saving of water up to 85-90%, as water is recycled and provide better yield as compared to conventional cultivation with almost zero environmental pollution. Hydroponics has been used efficiently to grow various crops such as lettuce, cucumber, tomato, herbs, and other types of flowers (Asao, 2012). It has its advantages over a conventional cultivating system, such as rapid growth, high productivity, easy handling, efficient water usage (Barbosa *et al.* 2015) and lesser fertilizer usage (Rana *et al.* 2011, and Cuba *et al.* 2015).Under hydroponics farming, the nutrient concentration of the aqueous solution is controlled and monitored to observe the symptoms and nutrient deficiencies or toxicity in the plant system (Adrover *et al.* 2013, and Cuba *et al.* 2015). The system can be customized to provide the plants with the correct amount of water, nutrients, and oxygen for optimal growth. Hydroponics has been very useful in toxicological studies in the accumulation of various contaminants in plants, to implement experimental studies in native and exotic crops for commercial, medicinal purposes, and also in traditional crops like vegetables and ornamental plants.

Importance and relevance of Hydroponics in urban farming

According to Tillman (2002), food security has arisen as a key concern in the current era, posing a critical challenge for the agriculture industry. (Hatifield *et al.* 2001; Hochmuth *et al.* 2001 and Hussain *et al.* 2014) .Furthermore, an estimated 690 million people are malnourished. According to research, cattle production uses over 80% of the worldwide agricultural area, requiring substantially more acreage than plant-based food farming. According to a study, over 30% of the world's food supply is wasted each year (Hussain *et al.* 2014). According to recent research, the majority of the world's population lives in cities, outnumbering those living in rural areas. In 2018, cities housed 55% of the world's population (Jones, 2012. According to another statistic, 30% of the world's population lived in cities in 1950 (Joseph, 2014). However, forecasts indicate that by 2050, this proportion will rise to 68% (Jovicich *et al.* 2004). Despite the fact that urban populations have grown fast, agriculture has been able to meet their growing demands by producing food that consumes more energy, land, and water, as well as emits more greenhouse gases. The main challenge is whether agriculture can sustainably meet the growing demands of urban populations while also fostering agricultural wealth and reducing poverty in both rural and urban areas (Khan F., 2018).

Advanced agriculture is now needed to boost productivity in order to solve the issue of reducing the weight of the poverty chain and concurrently countering demand for land and climate change concerns due to competition for limited resources (Nielsen *et al.* 2006). On the other hand, hydroponics is an essential component of modern farming, particularly when discussing "smart farming." It solves major issues with conventional farming practices and has certain advantages. When comparing hydroponics to traditional agricultural methods like soil and greenhouses, there are a number of advantages.

Hydroponic farming is known for its cheap water usage, often requiring up to 90% less water than traditional farming techniques (Ningoji *et al.* 2020). Compared to traditional soil growing, hydroponics may yield significantly more greens due to its precisely adjusted nutrient solutions (Okemwa E, 2015). Vertical farming system used as hydroponic culture that enhance the space available and also higher crop productivity per unit area.

In contrast to the horizontal hydroponic system, the VFS produced more crop per unit of culture space despite this reduction (Polycarpou *et al.* 2005). The results of the study suggest that VFS could be a good option in place of horizontal hydroponic development processes.

Pests and illnesses are less likely to be a problem with hydroponic systems, lowering the demand for chemical pesticides (Rouphael and Colla 2005). Finally, Hydroponics allows for continuous production throughout the year, independent of external weather conditions, guaranteeing a steady supply of fresh vegetables Sardare and Admane, 2013). Hydroponics often provides a better Return On Investment [ROI] than conventional farming methods because of its greater productivity and quicker harvest times (Schnitzler, 2012). Research findings indicate that hydroponic lettuce production has the potential to generate significantly higher yields per acre in comparison to soil-based cultivation, with reported increases of up to 20 times. In another study, the research findings indicate that implementing hydroponic cultivation methods and regulated environmental factors enabled uniform strawberry yield, irrespective of seasonal constraints (Tyson *et al.* 2004). These benefits demonstrate the practicality and longevity of growing hydroponically-cultivated leafy greens.

Advantages of hydroponic farming system-Resource Efficiency:

The optimization of resources like water, nutrients, and space is a key benefit of Hydroponics. Hydroponic farming techniques have been found to reduce water usage by up to 90% compared to conventional soil-based farming. Additionally, this method enables the recycling and reuse of nutrient solutions, promoting sustainability and reducing waste. The implementation of vertical farming techniques has been found to optimize space utilization, resulting in the ability to achieve high density crop production (Zekki *et al.* 1996).

Year-Round Crop Production: Hydroponics allows for cultivation throughout the year without being affected by seasonal or climatic constraints. Growers can utilize controlled environments to establish the ideal conditions for plant growth, encompassing temperature, humidity, light intensity, and nutrient concentrations. Maintaining a consistent and dependable food supply, decreasing reliance on imported goods, and improving food security are all important factors to consider (Jensen *et al.* 2012).

Increased Crop Yields: Research has demonstrated that hydroponic systems effectively regulate growth conditions, resulting in higher plant growth rates and greater crop yields compared to traditional farming techniques (Table 1). Research has shown that customizing nutrient delivery and optimizing the root zone environment can improve plant health and productivity (Grigas *et al.* 2019; Kumar *et al.* 2024).

Table 1: Soilless culture (hydroponics) v/s ordinary soil yields

Name of the Crop	Hydroponics equivalent per acre (Kg)	Agricultural average per acre (Kg)
Soybean	681	272
Potato	31751	3628
Beetroot	9071	4082
Cabbage	8164	5896
Cauliflower	13607	6803
Cucumber	12700	3175
Tomato	81646	4535
Peas	6350	907
French bean	19050 of pods for eating	—
Lettuce	9525	4082

Source: *Gautam et al. 2021.*

Environmental Sustainability: The utilization of Hydroponics has been found to reduce the adverse effects of agriculture. The elimination of soil dependency results in a reduction of soil erosion, loss of nutrients, and spoilage. Integrating

Hydroponics with sustainable practices, such as organic pest control, water recycling, and renewable energy sources, can contribute to a more environmental friendly approach to farming (Diehl *et al.* 2020).

Nutritional Quality and Flavor: The precise control of nutrient levels and growing conditions in hydroponic cultivation can improve crop quality and flavor. Hydroponic cultivation can be particularly noteworthy for specialty crops, herbs, and medicinal plants due to the potential to optimize specific compounds and active ingredients (Nikolov *et al.* 2023).

Pest and Disease Control: The soilless environment that hydroponics offers lowers the possibility of soil-borne illnesses and pests. Biological controls can be used to better apply Integrated Pest Management [IPM] approaches in hydroponics, reducing the demand for chemical pesticides. Produce is safer and plants are healthier as a result (Folorunso *et al.* 2023).

Urban Agriculture and Local Food Production: According to research, hydroponics is a good technique for urban agriculture since it enables the production of food in small areas such indoor facilities, rooftops, and vertical farms. It has been discovered that encouraging local food production improves access to fresh, locally grown crops and reduces transit distances. Additionally, there is an increase in local awareness and participation in sustainable food systems (Jensen *et al.* 1995).

Scientific Research and Innovation: Hydroponics provides a platform for agricultural innovation and scientific study. Researchers can test innovative methods, create better cultivars, and investigate new tactics for producing food in a sustainable manner. Continuous improvements in hydroponic farming techniques are made possible by the integration of automation, data analytics, and smart technologies. In contemporary agriculture, hydroponics is revolutionary because it offers higher productivity, sustainability, and efficiency. Because it may get around the drawbacks of conventional agricultural practices, it is a useful tool for addressing issues including environmental preservation, food security, and the rising demand for wholesome, premium products.

Technological intervention in Hydroponic Systems for Sustainable Crop Production: An artificial technique called hydroponic farming employs either organic or inorganic substrates to support plants and act as a reservoir for water and nutrients. The simplest and oldest method of soilless growing involves dissolving inorganic compounds in a vessel of water to provide all the necessary plant nutrients. Based on the substrate employed, hydroponic systems can be broadly divided into two categories: granular-substrate culture and soilless-solution culture (Li *et al.* 2018). The specifications of the various hydroponic farming systems currently in use, together with a list of the plants that thrive in each, are listed in Table 1.

Overview on Recent developments in Hydroponics

Artificial intelligence (AI)-based systems, IoT-automated growing methods, and smart home technology (domotics) have all recently become more popular and have useful uses in indoor hydroponic productions (Jain *et al.* 2025 and Souza *et al.* 2024). More people are beginning to investigate these growth methods for a variety of reasons due to the volume and accessibility of information available online, and both indoor and hydroponic cultures are becoming more and more popular among farmers (Souza *et al.* 2018).

Domotics for indoor cultivation- control tools

Building a facility for indoor production and hydroponic plants requires careful consideration of the concept. It is specifically necessary to take into account the location, size, type of plant being targeted, and equipment needed for the work at hand. Many specialized devices are needed to run an indoor conservatory and a hydroponic farming system. In order to create the ideal environment for plant growth, we will require horticultural lights with certain ranges, air movement aspirators, fans, humidifiers, heat producers, etc. Some of the control devices used today for better and more regulated production include thermo-hygrometers, which measure temperature and humidity, heating systems that control cooling or aspiration, and hygrostats, which control humidifiers or dehumidifiers. However, advanced Software-based controls with programs that can handle information collected by sensors and regulate the operation of lights, aspirators, humidifiers.

Table 1: Several technologies used in Hydroponic farming systems

Sl. No.	Hydroponic System	Characteristcs	Specific Plants	Reference
1	Nutrient Film Technique (NFT)	In the NFT system, plants' roots are continuously covered in nutrient-rich water, which allows them to absorb the nutrients they require. The extra liquid is gathered and put through a recycling procedure.	Leafy Greens Herbs, Strawberries, Beans Raddish, Cucumber	
2	Deep Water Culture	A nutritional solution that is continuously oxygenated by an air pump is used to suspend plant roots in this process. Long-term exposure to the aquatic environment allows the roots of plants that stay submerged in water to absorb more oxygen and nutrients. Deep water hydroponics systems like the Dutch bucket system are popular because they provide a controlled and fruitful environment for plant growth. To support the plant and allow its roots to reach a nutrient-rich solution, each bucket or container filled with an inert substance, such as coconut coir, is used. Because it is easy to use, scalable, and can be used with a variety of plants. Typically, the method is used in commercial	Lettuce, Herbs Leafy greens and Plants with large Root System Like Tomatoes, Cucumber and Peppers	
3	Drip System	The use of a drip system involves using a set of drippers to directly distribute nutritional solution to the plant's root zone. This technique involves dripping the solution into the preferred growing medium, like coco coir or perlite, and then letting it return to the container for possible usage.	Vegetables, Fruits, and Flowering plants	
4	Ebb and Flow (Flood and drain)	This invove the cyclic submersion of plants in a nutrient solution followed by subsequent drainage back in to the reservoir. The regular repitition of the cycle facilitation the privision of nutrient and oxygen to the roots	Tomatoes, Cucumbers, Peppers, Strawberries, Lettuce, Spinach , Radishes Beans	
5	Aeroponic	This invoves the supervision of plant roots in the air with intermittent nutrient solution application as a fine mist or spray in the roots. The observed phenomenon enables a higher level of oxygenation and nutrient uptake	Leay Greens, Herbs Strawberries, Capsicum, Cauliflower, Chilli	
6	Wick System	The wick system is a passive hydroponic design that is distinguished by its simplicity. In this experimental setup, the plants are situated within an inert growing medium and a wick constructed of a cotton rope is applied to facilitate the upward passage of nutrient solution from the reservoir of the root zone.	Small plants, Herbs and Low nutrient demanding plants	
7	Krakty Method	This technique is called the Kratky method which sees the polystyrene sheets suspended 3-4 cm above the water rather than floating on top to allow air to circulate around the plant roots. This approach removes the need for air stones in the trough as sufficient amounts of oxygen in the air is supplied to the roots.	Leafy greens Herbs	

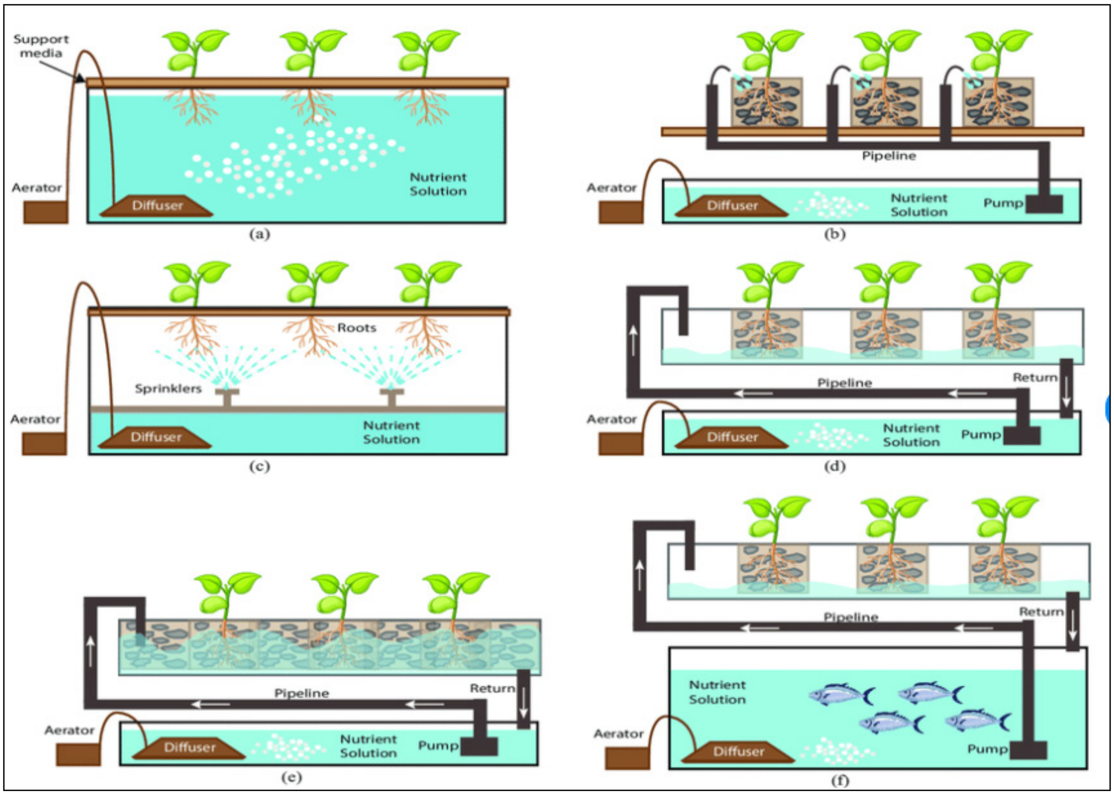

Fig. 1: Different types of hydroponic systems. **(a)** Deep Water Culture. **(b)** Drip System. **(c)** Aeroponics. **(d)** Nutrien Film Technique (NFT). **(e)** Ebb and flow. **(f)** Aquaponics

Integration of IoT in Vertical Farming

Vertical farming is a popular trend in Hydroponics that involves stacking multiple layers of plants in a vertical arrangement. This farming method saves space, reduces water usage, and increases yields per square foot of growing area. In response to increased demand for agricultural productivity, vertical farming is a new technology that aims to boost crop yield per unit of land. VF is a technically challenging and pricey crop production method that uses protected horticulture systems like glasshouses and controlled environment facilities along with numerous layers of growth surfaces and inclined production surfaces. Therefore, vertical farming (VF) requires a scientific approach that considers various elements, including lighting, crop nutrition, growing systems, energy efficiency, construction, and site selection (Gerwal *et al.* 2011). The Internet of Things (IoT)is used in vertical farming to monitor environmental conditions and collect data on individual plants. IoT systems use this information to formulate accurate recommendations for the amounts of light, water, and nutrients that should be provided to each plant. The prototype is equipped with sensors such as a light-detection resistor (LDR), soil moisture sensor (SMS), and LM35 temperature sensor (TMS), which together gather data on plant development and then analyze and show that data in a web application for optimal efficiency (Zhang *et al.* 2016). Using Internet of Things technology, sensors are used to monitor environmental and dietary factors including temperature, humidity, plant development, TDS, pH, and water level (Fig. 2).

Aquaponics: A sustainable hydroponics approach to the circular economy

It is the process of raising animals and plants—often fish—in close proximity to one another. Ammonia and other harmful fish wastes are converted by bacteria into nitrates and nitrites that are beneficial to plants. Since fish waste serves as the main source of food for aquaponics, it is important to comprehend this idea. Fish can swim in the water since the plants have filtered it. This strategy is advantageous since it reduces waste, which in turn saves money and biological resources (Nitu *et al.* 2024 and Amarsinghe *et al.* 2024).

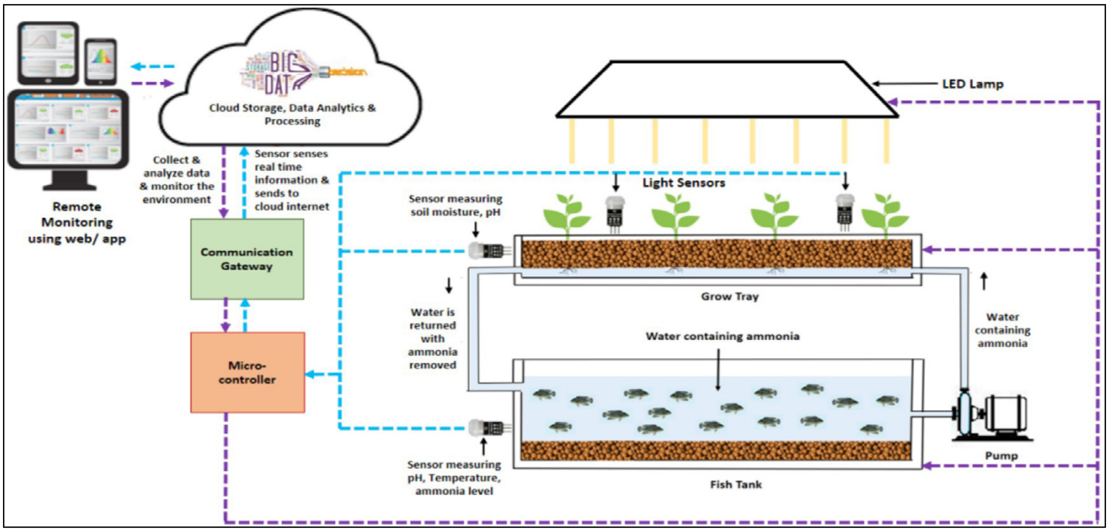

Fig. 2: Diagram showing IoT application in vertical farming (Source: Sowya *et al.* 2024)

Factors involved in an effective hydroponic system: Factors affecting seed germination and seedling establishment for hydroponics system: Regulated farming, specifically greenhouse food crop production, has been identified as a highly intensive form of cultivation that can effectively tackle the challenges of climate change, freshwater scarcity, and the increasing demand for food. The primary concern in the context of seedlings pertains to the challenge of insufficient germination and emergence. Controlling the factors that influence seed germination can improve crop development and reduce production costs by enhancing seed germination and emergence (Verma *et al.* 2024).

Factors influencing seed germination are tabulated in Table 2.

Effect of support system for plant growth in a hydroponic system

Rockwool has been identified as a commonly used growing medium in hydroponic systems. The material under consideration is produced by melting rock and spinning it into fibres. Its notable properties include high water retention capacity and adequate aeration. The use of Rockwool has been found to provide a stable structure for root development, which in turn promotes efficient nutrient uptake. The versatility and accessibility of this substance make it suitable for various plant species (Fylladitakis, ED, 2023).

Coco coir: 'Since coco coir is made from coconut husks, using it as a growing medium is an environmentally responsible and sustainable approach. The substance being studied demonstrates favorable water retention properties and promotes sufficient aeration. It has been discovered that using coco coir promotes root development and fosters the growth of beneficial microorganisms. One of the subject's acknowledged qualities is its capacity to buffer nutrient solutions, which guarantees that plants receive the right amount of nutrients.

Peat moss is a frequently used growth substrate in hydroponic systems. The material exhibits exceptional water-holding properties and demonstrates a high capacity for moisture retention. Improper soil management can lead to compaction, which can impede the growth of roots. The acidity of peat moss necessitates careful monitoring and adjustment of the nutrient solution's pH. Adding perlite or vermiculite is a common practice to enhance aeration in the medium (Najera *et al.* 2022).

Expanded clay pellets: The lightweight and aerating properties of expanded clay pellets, also referred to as hydroton or clay pebbles, are making them highly interested in the hydroponics field now. Additionally, these pellets have been noted to provide effective drainage. They exhibit a pH value of 7, indicating a neutral nature. Plant roots require stability and efficient oxygen exchange, which specific structures can facilitate. The water-holding capacity of these materials is limited, which may necessitate more frequent irrigation.

Biochar: Biochar production involves subjecting organic matter to high temperatures in an oxygen-

Table 2: Factor affecting Seed germination

Factors	**Effects of Seed germination**
Temperature	Seed germination depends on precise temperature conditions. The temperature range best suited for plant growth influences germination. According to research, maintaining optimal temperature conditions might improve seed germination speed and uniformity. Maintaining the correct temperature for certain seedlings during germination in a hydroponic system is critical for monitoring (Dutta *et al.* 2025)
Light	The role of light on seed germination and early seedling development is well understood in the field of plant studies. Most seeds germinate when exposed to light, but certain seeds may require a time of darkness to germinate. The proper intensity and duration of light are critical in hydroponic systems. Artificial grow lights, such as LED or fluorescent lights, can supply the seedlings with the necessary light energy (Dutta *et al.* 2024 and Farhan *et al.* 2025).
Water and Moisture	Hydroponic systems use water as the major medium for delivering plant nutrients. Adequate water and moisture conditions are required for seed germination. Excess water can cause rotting or damping-off illnesses, so keep the seeds regularly moist but not unduly saturated. Maintaining the proper moisture balance in the growth medium is critical for good seedling establishment. Wetting the chosen medium before sowing the seeds is advised, but not excessively. To ensure proper germination, keep the seeds at a steady moisture level. However, it is vital to note that too much water might stymie the growth of the initial branches and roots, preventing the plant from establishing itself. It is also recommended to maintain a consistently moist environment for the medium during the germination process and the initial days following sprouting. Overwatering must be avoided to prevent medium saturation.
Oxygen	Oxygen availability is a crucial aspect that affects seed germination and root development in hydroponic systems. The respiration process of seeds necessitates oxygen, and oxygen in the growth medium is a critical factor in ensuring the successful establishment of healthy seedlings. Using an inert growing medium, uch as perlite, vermiculite, or rockwool, is common in hydroponic systems. This method facilitates optimal oxygen exchange. Adequate oxygen supply to the roots is crucial to nutrient solution aeration.
Nutrients	Some nutrients are included in seeds to aid in their initial growth, but more nutrients are required for seedlings to develop healthily. Hydroponic systems need a balanced nutrient solution that includes micronutrients like iron, zinc, and manganese in the right amounts as well as vital macronutrients like potassium, phosphorus, and nitrogen. Maintaining the ideal pH level of the nutrition solution and making sure that the nutrients are balanced properly will encourage the growth of seedlings to their full potential
pH Level	The measurement of acidity or alkalinity in a solution is commonly referred to as pH. Plants' optimal growth depends on their specific pH requirements, which vary among plant species. Maintaining an appropriate pH range within the nutrient solution is crucial for successful germination and establishment of seedlings in a hydroponic system. Research has shown that the optimal pH range for most plants is slightly acidic to neutral, with a range of approximately 5.5 to 6.5. Frequent monitoring and adjustment of the pH level in the nutrient solution is crucial in establishing an ideal growth environment for the seeds
Seed Quality	The role of seed quality and viability is crucial in determining the success of germination. Using premium seeds from trustworthy sources enhances the probability of prosperous germination and seedling establishment. In order to maximize the germination potential of seeds, it is important to use fresh, disease-free, and properly stored seeds (Rahman *et al.* 2021)

free environment, producing carbon-rich material with a porous structure. The material exhibits outstanding characteristics of water retention and aeration. Research has shown that applying biochar can enhance the capacity of the root zone to retain nutrients and promote microbial activity. Moisture regulation is one of the benefits of this technique, which also mitigates the risk of overwatering. The low nutrient-holding capacity of the soil may necessitate supplementary fertilization (Polwaththa, *et al.* 2024). Classification of Hydroponics based on the usage of substrates in the medium is listed in Table 3.

Effect of Nutrients in Hydroponics and its Importance

The availability of 17 vital nutrients is the primary

Table 3: Hydroponic system based on substrate employed as a medium

Hydroponic System	Growing Medium	Advantage	Disadvantage
Solution Culture			
Nutrient Film Technique	No solid medium, a thin film of nutrient solution flows over the roots	1. Water and nutrient efficiency Oxygenation of roots 2. Rapid plant growth 3. Space efficiency 1. Reduced pests and diseases	2. System failure risks 3. pH and nutrient balance maintenance 4. Limited root support 5. Sensitivity to temperature fluctuations: 6. Initial setup and cost
Deep water culture	No solid medium, roots suspended in nutrient solution	1. Increased oxygenation 2. High growth rates 3. Water efficiency 4. Nutrient control 5. Reduced pests and diseases	1. Equipment and setup cost Monitoring and maintenance 2. Power dependency 3. Root diseases
Aeroponics	No solid medium, roots suspended in air, misted with nutrient solution	1. Water and nutrient efficiency 2. Oxygenation of roots 3. Rapid plant growth 4. Space efficiency 5. Reduced pests and diseases	1. System complexity and maintenance 2. Vulnerability to power outages 3. Sensitivity to environmental factors 4. Initial setup and cost 5. Risk of root drying
Medium Culture			
Rockwool	Rockwool fibres provide support and moisture retention	1. Excellent water retention 2. Good aeration for root development 3. pH stability for optimal nutrient uptake 4. Insulation against temperature fluctuations 5. Disease-resistant and sterile medium 6. Reusable multiple times 7. Suitable for a wide range of plant species	1. Initial high cost of the material 2. Requires proper pH adjustment 3. Limited availability in some regions 4. Environmental impact due to its production process
Perlite	Lightweight and porous material allowing good aeration	1. Aeration 2. Lightweight 3. pH-neutral 4. Reusability	1. Dust and floating particles 2. Limited cation exchange capacity 3. Fragile and breakdown over time 4. Limited structural support
Vermicultite	Mineral-based medium with moisture retention and drainage properties	1. Water retention 2. Aeration 3. Insulation 4. Nutrient Retention 5. pH-neutral	1. Potential for root rot 2. Cost and availability 3. Limited reusability 4. Limited structural support Compaction
Coco Coir	Derived from coconut husks, it provides water retention and aeration.	1. Aeration 2. Lightweight 3. pH-neutral 4. Reusability	1. High cost of the material 2. Limited cation exchange capacity 3. Fragile and breakdown over time 4. Limited structural support

Expanded clay pebbles	Lightweight clay pebbles for aeration and support	1. Excellent drainage properties 2. Lightweight and easy to handle 3. Provides good aeration for root development 4. pH-neutral and inert material 5. Reusable multiple times 6. Suitable for a variety of plant species	1. High initial cost compared to other media 2. Requires regular cleaning to prevent clogging 3. Limited water-holding capacity may require more frequent watering 4. It can be dusty and require rinsing before use 5. It may require additional support structures for heavy 6. Plants

determinant of plant growth. It can be further divided into macronutrients and micronutrients. It is impossible to exaggerate the significance of either for plant development and nutrition. This include micronutrients such as iron, manganese, zinc, boron, molybdenum, chlorine, copper, and nickel as well as macronutrients such as carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium. Plants acquire carbon, hydrogen, and oxygen through natural means, specifically from the air and water they consume, with the remainder obtained from the soil. The roots obtain nutrients from nutrient solutions or aggregate media in hydroponic systems. Research has shown that hydroponic systems are comparatively less tolerant than soil-based systems, and any issues related to nutrients can rapidly manifest plant symptoms. The criticality of the nutrient solution composition and regular monitoring of the nutrient solution and plant nutrient status is a significant aspect to consider. The major salt deficiencies that a hydroponic system may encounter include nitrogen, calcium, iron, magnesium, and boron deficiencies. The detrimental effects of soluble salts have been attributed to various factors, including but not limited to over-fertilization, suboptimal water quality, gradual accumulation of salts in the aggregate media, and inadequate drainage. Insufficient leaching during the process of fertigation in Hydroponics can lead to the accumulation of soluble salts in the medium due to water evaporation (Ramakrishnam *et al.* 2022). Nutrient antagonism and interaction is a crucial parameter that warrants serious consideration in the context of hydroponic systems. Research suggests that plants tend to absorb nutrients proportionally to their presence in the nutrient solution.

The phenomenon of nutrient uptake in excess leading to a higher uptake of one nutrient at the cost of yet another has been observed and is classified as nutrient antagonism. The nutrient levels in the nutrient solution may not necessarily guarantee optimal plant growth and development. Despite sufficient nutrient supply, plant nutrient deficiency may still occur (Rama krishnam *et al.* 2022). Nutrients commonly employed in nutrient solutions of hydroponic growing systems, their functions, and the diseases associated with their deficiency in plants are tabulated in Table 4.

Effect of physical factors: Light: The significance of light in photosynthesis cannot be overstated, as it is the primary source of energy for plants to synthesize organic compounds. Through this process, plants convert light energy into chemical energy, which is then utilized to support their metabolic processes and promote growth. Artificial lighting systems such as LED lights can be utilized in smart Hydroponics to regulate light's intensity, spectrum, and duration meticulously. The optimization of light settings is a crucial factor in plant growth, as it enables growers to provide the appropriate amount and quality of light that is required for each growth stage. The light requirements of plants vary depending on the species, with some requiring specific amounts of red and blue light. Light regulation in smart Hydroponics is crucial for providing plants with adequate energy for photosynthesis, which leads to healthy growth, strong development, and enhanced yield (Rao *et al.* 2024).

Temperature: Temperature plays a significant role in plant growth and metabolic processes. In smart Hydroponics, the temperature can be precisely regulated to create an ideal plant environment. Each

Table 4: Nutrient used in hydroponic nutrient solutions

Nutrient	Classification	Function in Plant	Major Source	Deficiency System
Nitrogen (N)	Macro	Essential for growth, leaf development, and protein synthesis	Nitrate (NO_3^-) and Ammonium (NH_4^+)	Stunted growth, yellowing leaves
Phosphorus (P)	Macro	Key role in root development, energy transfer, and flower/ fruit formation	Phosphate (PO_4^-)	Poor root growth, purplish leaves
Potassium (K)	Macro	Vital for overall plant health, nutrient uptake, and disease resistance	Potassium (K^+)	Weak stems, yellowing edges of leaves
Calcium (Ca)	Macro	Essential for cell wall structure and overall plant stability	Calcium (Ca_2^+)	Blossom end rot, stunted growth
Magnesium (Mg)	Macro	Crucial for chlorophyll production and enzyme activation	Magnesium (Mg_2^+)	Yellowing between leaf veins
Sulfur (S)	Macro	Important for protein synthesis and overall plant vigor	Sulfate (SO_4^-)	Yellowing of younger leaves
Iron (Fe)	Micro	Required for chlorophyll formation and enzyme functions	Iron (Fe_2^+ and Fe_3^+)	Yellowing leaves with green veins
Manganese (Mn)	Micro	Necessary for photosynthesis and enzyme activities	Manganese (Mn^{+2})	Yellowing between leaf veins
Zinc (Zn)	Micro	Essential for enzyme activation and hormone regulation	Zinc (Zn_2^+)	Stunted growth, malformed leaves
Copper (Cu)	Micro	Important for enzyme functions and photosynthesis	Copper (Cu_2^+)	Wilting, leaf discoloration
Molybedneum (Mo)	Micro	Required for nitrogen fixation and enzyme activity	Molybdate (MoO_4^-)	Yellowing of older leaves
Boron (B)	Micro	Vital for cell division, pollen formation, and sugar transport	Borate (BO_3^-) Brittle and distorted leaves	Brittle and distorted leaves
Nickel (Ni)	Micro	Plays a role in nitrogen metabolism and enzyme function	Nickel (Ni_2^+)	Reduced growth, leaf deformation

plant species has an optimal temperature range for growth and development, including germination, root growth, and flowering. Maintaining the appropriate temperature range can enhance enzymatic activity, nutrient uptake, and overall plant performance. Smart hydroponics systems often use sensors and automated controls to monitor and adjust temperature levels, ensuring that plants are kept within their preferred temperature range (Rao *et al.* 2024).

Humidity: The term humidity pertains to the quantity of water vapour in the atmosphere. The careful management of humidity in smart Hydroponics can lead to the creation of an optimal growing environment. The impact of high humidity levels on transpiration rates in plants has been studied, with findings suggesting potential benefits for certain plant species during the vegetative growth stage. Research has shown that high humidity levels can lead to the development of fungal diseases. Low humidity has been found to cause rapid moisture loss in plants, potentially resulting in water stress. Incorporating humidifiers, dehumidifiers, or ventilation systems in smart hydroponics systems enables the maintenance of accurate humidity levels. The manipulation of humidity levels by growers can facilitate an optimal environment for plants, fostering robust growth and mitigating the likelihood of pathogenic infections. In smart Hydroponics farming, the ability to control and optimize physical factors gives growers greater precision and flexibility in creating an ideal growing environment. By fine-tuning light, temperature, and humidity, growers can mimic optimal conditions for specific plant species, growth stages, and environmental preferences. This level of control allows for more efficient resource utilization, improved plant health, and, ultimately higher yields in hydroponic cultivation.

Advantages of hydroponic smart farming

Increased Yield: Precise control over environmental factors promotes optimal plant growth. Nutrient-rich solutions lead to healthier and more vigorous plants and higher yields than traditional soil-based cultivation methods.

Water Efficiency: Hydroponics uses up to 90% less water than soil-based farming. Recirculating systems minimize water wastage and evaporation. Water is efficiently delivered directly to plant roots, reducing water usage.

Space Efficiency: Hydroponic systems are highly space-efficient and require less land. Vertical growing techniques maximize production in limited areas. Suitable for urban farming, rooftops, or areas with limited agricultural space.

Controlled Environment: Precise control over light, temperature, humidity, and nutrient levels is needed. Ideal growing conditions tailored to specific plant requirements. Year-round cultivation regardless of seasonal limitations. Reduced *Environmental Impact*: Less land and water usage minimize the ecological footprint. Decreased need for pesticides and herbicides. Minimized soil erosion and nutrient runoff, preserving soil quality.

Superior Plant Quality: Enhanced nutrient delivery promotes healthy plant growth. Higher concentrations of desired compounds in herbs and medicinal plants. Improved flavour, aroma, and nutritional value. Rapid Growth and Harvest: Plants grow faster in Hydroponics due to optimized growing conditions. Shorter crop cycles and faster harvest times. Quick turnaround and increased production capacity. Disease and Pest Control: Soil-free environment minimizes the risk of soil-borne diseases and pests. Easier monitoring and management of plant health. Reduced reliance on chemical treatment.

Flexibility and Scalability: Hydroponic systems can be scaled up or down to suit different needs. Versatile setups accommodate various plant species—adaptability to different growing environments and locations. By harnessing these advantages, Hydroponics could offer a highly efficient and sustainable method of cultivation, enabling growers to maximize yields, optimize plant quality, and minimize environmental impact.

Future Goal: Achieving 30% food sustainability by 2030 with only 1% arable land requires careful planning, innovation, and the implementation of various strategies. Some key considerations for achieving this goal include: Hydroponics in hospitals: Integrating mobile hydroponic systems in hospitals is a potential future direction for Hydroponics. This approach is considered innovative and can improve nutrition and patient care. Culturing high-value plants rich in essential nutrients, minerals, vitamins, and therapeutic compounds can improve the quality of meals in hospitals. This targeted nourishment may support patients' recovery and overall well-being. Integrating a mobile hydroponic system with vertical farming techniques can optimize cultivation in a small area, allowing for efficient use of space in various settings such as roof-top gardens, balconies, or dedicated indoor spaces. Implementing this approach guarantees an uninterrupted provision of superior plant specimens such as herbs, leafy greens, or medicinal plants. Using these plants in cooking, teas, or extracts can serve as a natural source of remedies and supplements for patients, which may aid in fulfilling their dietary needs. Hydroponics provides a controlled environment that enables year-round cultivation, reducing reliance on seasonal produce and potential supply fluctuations.

Vertical Farming and Rooftop Gardens: Vertical farming and rooftop gardens should be extensively explored due to the limited availability of land. Vertical farming involves growing crops in vertically stacked layers, enabling optimal utilization of space. Establishing rooftop gardens on buildings has been identified as a potential method for expanding areas available for food production. The practice of indoor agriculture: It encompasses greenhouse systems, can facilitate crop production throughout the year while safeguarding crops from unfavourable weather conditions. The practice of Controlled Environment Agriculture (CEA) entails meticulously regulating environmental variables, including light, temperature, humidity, and CO_2 concentrations, to facilitate the most favourable conditions for plant growth. Implementing CEA technologies has potentially improved productivity and resource efficiency (Miller *et al.* 2025).

High-Yield Crop Selection: Hydroponic system studies emphasize the importance of prioritizing high-yield crops that can provide maximum output within a confined space. The prioritization of crops with shorter growth cycles, higher nutritional value, and greater demand is a crucial aspect of agricultural research. This study aims to investigate and determine appropriate crop cultivars that are well suited for the climatic conditions of Singapore and can be cultivated effectively through hydroponic or other advanced agricultural methods.

Efficient Resource Utilization: The optimization of resource utilization can be achieved by implementing smart irrigation systems, water recycling, and nutrient management strategies. Implementing techniques such as drip irrigation, fogging, or precision fertigation can reduce water and nutrient wastage. Research has shown that the implementation of recirculating hydroponic systems can result in a significant reduction in water consumption.

Agro-technology and Automation: Implementing advanced agro-technology and automation can enhance productivity and decrease labour demands in the agricultural sector. The implementation of IoT-based systems, sensors, and data analytics are being researched to monitor and control environmental parameters, detect crop health issues, and optimize resource usage. Implementing automated processes, such as robotic seeding, harvesting, and maintenance, has the potential to address labour limitations.

Sustainable Energy Sources: The implementation of advanced agro-technology and automation has been shown to impact productivity and labour requirements in agriculture positively. Implementing IoT-based systems, sensors, and data analytics can be utilized to monitor and control environmental parameters, detect crop health issues, and optimize resource usage. Implementing automated processes, such as robotic seeding, harvesting, and maintenance, can potentially address labour limitations.

Collaboration and Partnerships: Promoting collaboration among government agencies, research institutions, industry stakeholders, and the community is essential. Promoting knowledge sharing, research collaborations, and publicprivate partnerships is essential in driving innovation, exchanging best practices, and collectively working towards achieving food sustainability goals (Verma *et al.* 2024).

Education and Awareness: This study aims to increase public awareness and knowledge regarding food sustainability and the advantages of locally cultivated produce. Research suggests that urban farming initiatives in schools, community centres, and residential areas can involve citizens in sustainable food production and create a sense of food security.

Policy Support and Incentives: Research suggests that implementing supportive policies and incentives can effectively promote urban farming initiatives. Research suggests that providing grants, subsidies, tax incentives, and streamlined regulatory processes can effectively encourage investment in urban agriculture. The study aims to investigate the impact of policies on fostering innovation, research, and the adoption of sustainble farming practices.

Food Waste Management: The effective management of food waste is a crucial area of research that requires attention. The promotion of composting, recycling, and utilising food waste as a valuable resource for bioenergy or fertilizers is recommended. The reduction of food waste has the potential to alleviate the burden on resources and foster a more sustainable food system (Pandey AK, 2025). By considering these factors and implementing a comprehensive approach that encompasses technology, innovation, collaboration, and sustainable practices, locals can work towards achieving their 30% food sustainability goal by 2030, despite limited arable land availability.

Constraints on Hydroponic Farming Ecosytem

1. High capital investment

Commercial cultivation of vegetable crops through soilless farming requires huge capital investment (Resh, 2013).

2. Technicians and skilled labours

Soilless culture is an advanced and modern technology-based vegetable cultivation that requires skilled labours to handle these modernized equipment's.

3. Pathogenic injuries

The nutrient solution is circulated regularly to all plants and excess water is collected back in the tank. In this closed system once a plant gets affected by a pathogen it's very difficult to eradicate and it gets transmitted rapidly to other healthy plants (Ikeda *et al.* 2001).

Water and electricity

Successful soilless vegetable farming is achieved by proper water and electricity supply to the automated devices. Power failure and fewer water source may cause the failure of commercial farming under greenhouses.

CONCLUSION

Hydroponics holds immense promise for the future of agriculture. This innovative cultivation method offers a range of advantages that address the challenges faced by traditional farming practices. With its ability to maximize resource efficiency, enable year-round crop production, and enhance yields, Hydroponics has the potential to revolutionize the way we grow food. By utilizing Hydroponics, we can optimize water, nutrients, and space, reducing waste and promoting sustainability. The controlled environments of hydroponic systems allow for precise control over growing conditions, resulting in accelerated growth rates and higher crop yields. This, in turn, contributes to food security, reduces dependence on imports, and increases the availability of fresh, locally-grown produce. Moreover, Hydroponics offers a pathway to environmental sustainability by reducing soil erosion, minimizing chemical inputs, and integrating with eco-friendly pest control methods. It also opens up possibilities for urban agriculture, allowing for food production in limited spaces and bringing farming closer to urban centres. As technology advances, integrating smart technologies, automation, and data analytics with Hydroponics further enhances its potential. This integration enables real-time monitoring, precise control, and automation of various processes, leading to greater efficiency, reduced labour requirements, and improve overall productivity.

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