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Review Article

A COMPREHENSIVE REVIEW OF HYDROPONICS FOR SUSTAINABLE AGRICULTURE

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Agriculture has been the backbone of humankind, but conventional farming is becoming inefficient to face current challenges. Soil-based farming has worked well for thousands of years but is now confronted with rising constraints that will also create concerns regarding sustainability. Problems regarding soil loss, water supply and dependence on a vast amount of chemical fertilizers and pesticides have played a dramatic role in crop production. Conventional farming is a very large consumer of land and water, and with their growing lack, farm sustainability is on the decline. For example, soil degradation and loss of fertility due to erosion and nutrient loss remain one of the most important challenges to agriculture in the contemporary period (Gomiero, 2016).

Excessive application of chemical inputs, for instance, fertilizers and insecticides, causes acidification of the soil and pollution of water bodies, which further pollute the environment. This has led to reduced yields and enhanced vulnerability to pests and diseases (Duveiller *et al.*, 2007). Furthermore, plant-borne pathogens and nematodes can cause substantial losses in crop production, with conventional means having limited protection against these hazards (Mendoza-de, 2022). The dependence on rain-fed agriculture in much of the globe, including India, adds to the menace. Irregular rainfalls and climatic change impact crop cycles, resulting in reduced yields (Raza *et al.*, 2019).

Conventional farming is also labour-intensive, especially in nations such as India where smallholder farmers are prevalent. With labour becoming costly and rural communities moving to urban areas seeking better prospects, the labour-intensive characteristics of conventional agriculture hinder its sustainability (Charania and Li, 2020). Generally, conventional agricultural practices, although adequate in the past, cannot anymore keep up with the increasing challenges of the modern world.

Challenges posed by increasing population and diminishing arable land

The global population is likely to hit about 10 billion by the year 2050, posing a serious threat to world food security. In India, the urgency is greater still since the nation is likely to become the most populous nation on the planet by 2027. Unprecedented pressure on agriculture to produce more food on less land is caused by the rapid population growth. However, land degradation, industrialization, and urbanization are reducing the amount of arable land. According to Machiwal *et al.* (2023), for instance, India's arable land has significantly decreased, a situation that is made worse by salinization and desertification in regions like Rajasthan and Gujarat.

The loss of farmland is a global problem; however, few places are becoming urban at such alarming rates compared to developing countries (Nath *et al.*, 2015). Not only is climate change causing erratic weather patterns, increasing instances of a typical events like droughts and floods, and shifting pest and disease environments, but it is also affecting agricultural productivity (Reddy *et al.*, 2015).

In addition to environmental considerations, water availability is one of the most pressing problems faced by farmers worldwide. Over 70% of freshwater withdrawals worldwide are used for agriculture, although in many nations, substantial amounts of water are lost due to inefficient irrigation systems.Aquifers in a number of Indian states are in danger of collapsing due to the disastrous scenario caused by excessive groundwater extraction for agriculture (Hora, 2022).Because of these difficulties, it is necessary to look into different farming methods that can produce more food using fewer natural resources.

Hydroponics as a solution for sustainable farming and food security

Hydroponics, a method of plant culture that uses no soil, offers one of the most plausible alternatives to the limitations of traditional agriculture. Instead of using traditional soil-based agriculture, hydroponics provides an alternative solution where crops are grown in a dissolved nutrient solution. Hydroponics is water efficient, using potentially less water to produce crops than conventional farming. It can also be implemented within a controlled environment to produce crops in areas where there is a limited amount of land. Hydroponic farming has shown that water savings can be up to 90% more than traditional agriculture in arid regions (Qadir *et al.*, 2007), making it a feasible solution for use in areas that are already suffering water shortages.

The innovation of hydroponic systems has mainly been prompted by the desire for more environmentally friendly farming approaches that overcome the challenges of traditional farming. Water is recycled in a hydroponic system, and therefore less water is required to cultivate crops. Since plants are cultivated in a solution of nutrients, hydroponics minimizes most of the issues associated with

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soil, like pathogens, inefficient drainage, and erosion (Ranjha *et al.*, 2024). This process also provides fine control over the nutrients supplied to plants, maximising growth conditions and enhancing yield (Mourouzidou *et al.*, 2023).

In addition, hydroponic cultivation can be practised in urban areas, enabling crops to be produced near the consumers, saving transportation costs and reducing environmental concerns. Vertical farming, which is a form of hydroponic system that entails growing plants in layers, makes optimal use of space and can be incorporated into urban development (Akintuyi, 2024). Such urban agriculture is especially vital in nations such as India, where fast urbanization is decreasing the land available for farming. By local production of food within urban areas, hydroponics has the potential to enhance food security and minimize the carbon footprint linked to food transportation from rural regions (Eigenbrod and Gruda, 2015). Besides the environmental advantages, hydroponics has the potential for increased crop yield compared to conventional farming. A study by Sharma and Kumar (2023) proved that hydroponic crops are able to yield faster growth rates and increased production because of the controlled delivery of nutrients and conditions for growth.

Further, hydroponics enables year-round production since the controlled environment shields crops from seasonal changes as well as weather-related interference. Hydroponics also possesses a potential use for food cultivation in non-conventional environments, including arid or barren areas, and even for use in space missions. NASA has also been exploring hydroponic methods for food growth in space, as it provides a feasible means to support astronauts during extended missions (Oluwafemi *et al.*, 2018).

The purpose of this research article is to study the implementation of automation technologies in hydroponic systems for improving efficiency in operations, yield of crops, and sustainability in Indian agriculture. In addressing the gaps in existing research on automated hydroponic practices, this research aims to explore new control instruments, data acquisition schemes, and IoT integration, thereby presenting an integrated framework for designing fully automated hydroponic systems.

1. Challenges of traditional agriculture

Conventional soil-based farming has been the bedrock of Indian food cultivation for centuries, but it is beset by a variety of issues that jeopardize its sustainability and productivity. The problems arise from a series of factors, ranging from soil health, geographical limitations, and labour requirements to climate uncertainty.

1.1 Soil-based agriculture's issues

One of the largest problems common to conventional farming is the occurrence of disease pathogens in soil. Soil-dwelling pathogens like wilt, root rot, and blight are capable of inflicting huge damage to plant growth and yield and inducing loss for the farmer (Katan, 2017). Inadequate soil management techniques can make these situations worse by promoting the growth of these dangerous species. Nematodes, which are microscopic worms that infest plant roots, are another problem. They are a common disease that results in reduced plant growth and lower agricultural yields. Chemical pesticides are primarily used in conventional farming practices to control these pests; however, repeated applications of these chemicals can degrade soil and lead to the formation of resistant insect populations (Abrol and Shankar, 2014).

Another issue endangering India's traditional farming practices is soil drainage. Waterlogging brought on by poor drainage affects crop productivity and root growth. During the rainy season, soil erosion brought on by inadequate drainage systems lowers the fertility of agricultural land. After soil erosion, the top surface of soil loses its premium soil, which contains nutrients needed for crops, and henceforth, it adds more sediments to water bodies. Erosion also devastates nearby ecosystems. Due to outdated and labour-intensive methods, farmers are also lagging behind in terms of soil health and erosion control, which are essential for agriculture to succeed (Kansanga *et al.*, 2019)

1.2 Difficulty in crop cultivation due to geographical and topographical constraints

Geographical and topographical constraints also play a significant role in India's conventional agriculture. Steep slopes, rock land, or poor soil can be difficult for conventional farming. Geographical constraints, in the view of Shah *et al.* (2019), can constrain the access to resources such as water and sunlight, which are essential to plant growth and agricultural yield. Particularly, hilly areas face difficulty in handling water and soil conservation, thus resulting in diminishing agricultural viability. For example, the climatic variability between the peninsular south and the north plains requires different agricultural practices and thus it is not simple for farmers to change their practices based on changing environmental conditions. The issue of adaptability is especially evident in smallholder farming systems since farmers might lack access to information and capital to change to more suitable crops or practices (Aniah *et al.*, 2019).

1.3 Climate-related challenges

On account of global warming, the greatest challenge to conventional farming is irregular rainfall. Floods or droughts are the byproducts of more erratic monsoon trends in certain regions of India, like Vidarbha in the Maharashtra state. Because the monsoon rains were primarily what farmers used to irrigate, uncertainty is extremely negative towards agricultural output. Rain uncertainty may be capable of disrupting planting calendars and disrupting vegetation growth, ultimately impacting food security.

Soil fertility problems are also a climatic issue confronting conventional farming. In the absence of soil care in subsistent cropping, there is a condition of nutrient loss, compromising soil integrity as well as agricultural productivity. For areas such as Vidarbha, crops normally planted are only one type; without crop rotation, nutrient loss becomes greater, further reducing the soil fertility. Increased temperature that is associated with global warming also affects the fertility of crops because most conventional crops cannot tolerate high temperatures (Orsini *et al.*, 2020).

Traditional Indian agriculture is facing serious issues with complex and interconnected problems.Soil health problems, soil properties, and climatic uncertainty present possible threats to the sustainability of conventional agriculture. Solving all of these issues requires new solutions that enhance agricultural resilience in addition to promoting sustainable agriculture.

2. Hydroponics: A modern farming solution

A new approach to farming has been a revolutionary solution in contemporary agriculture, particularly in the context of increasing challenges against conventional soil-based farming practices. Hydroponics is an innovative method for cultivation that enables plants to develop in a solution of nutrients present in water, devoid of soil but surrounded by a controlled system for growth and yield improvement. According to Shanthi *et al.* (2023), hydroponics was a cost-effective substitute method for the cultivation of medicinal plants..

2.1 Definition and Methods

Hydroponics is the growing of plants without soil, with the mineral nutrient solutions dissolved in an aqueous solvent. It has become a popular method because it allows for efficient utilization of resources while attaining high crop yield. Different hydroponic methods have been established, such as Deep Flow Technique (DFT) and Nutrient Film Technique (Figure 1), each with different advantages and uses.

DFT is a method of submerging the plant roots in a running nutrient-rich water solution. DFT ensures consistent delivery of nutrients and oxygen to the plants, which is required for growth. DFT works best with leafy greens and herbs and is hence good enough for commercial crops (Abu-Izneid *et al.*, 2024).

Figure 1. NFT System (Wadood *et al.*, 2024)

Table 1. Hydroponic systems, characteristics, and specific plants

Hydroponic system	Characteristics	Specific plant
Deep Water Culture (DWC)	Roots submerged in nutrient solution; oxygenated via air pumps	Lettuce, Spinach, Kale
Nutrient Film Technique (NFT)	Thin film of nutrient solution flows over roots; good aeration	Basil, Lettuce, Herbs
Ebb and Flow	Periodic flooding and draining of nutrient solution	Tomatoes, Peppers, Herbs
Drip System	Nutrient solution dripped directly to roots	Strawberries, Cucumbers
Aeroponics	Nutrient mist sprayed onto roots; plants suspended in air	Leafy Greens, Herbs
Wick System	Nutrient solution drawn to roots by capillary action; low-tech system	Herbs, Lettuce

Nutrient Film Technique (NFT), however, is made up of a thin layer of nutrient solution flowing over the roots of the plants, which are contained within an inclined channel. The roots take up the essential nutrients as well as being exposed to air to allow for respiration. NFT is reputed for its high efficiency in the use of nutrients and space, thus being best suited for urban agriculture where space is scarce. Although both techniques ensure effective delivery of nutrients and water usage, aeroponics tends to lead to faster growth cycles and can be especially valuable in applications such as vertical farming (Wadood, 2024). Table 1 gives an overview of some different hydroponic systems along with their details.

3 Advantages

Because of the extensive dependence upon soil water in traditional agriculture, much water is lost through evaporation and runoff. In hydroponics, however, the utilization of water can be up to 90% less than that in traditional agriculture. Food production can thus be made possible in arid areas in a sustainable manner.

The regulated atmosphere that hydroponics offers is another benefit. Environmental factors such as pH, humidity, temperature, and nutrient content can be controlled by farmers to maximize plant growth (Figure 2). This degree of control reduces the need for chemical pesticides and herbicides by reducing the hazards associated with illnesses and pests. Accordingly, crops grown hydroponically are healthier and might have more nutritional value than crops grown in soil (Abu-Izneid *et al.*, 2024.

Figure 2. Integrated pest management (IPM) techniques (Wadood *et al.*, 2024)

The high yields with hydroponics have been realized through various studies. Studies have indicated that crops produced hydroponically can yield twice as much as those grown in soil, or perhaps 10 times as much. Food security concerns will be lessened with such increased productivity, particularly in densely populated and less populated places.

3.1 Applications

Hydroponics has been successfully used in regions with poor soil or severe weather conditions.For instance, in Israel, a nation with severe drought and water constraint, hydroponic systems have revolutionized agriculture.Israel has become a leader in agricultural technology, effectively growing a wide range of crops using hydroponics.These techniques showed how hydroponics can improve food output and water management while lowering environmental stress. Hydroponics is a good alternative for local food production within constrained land areas in urban environments. With hydroponic installations, rooftop gardens and vertical farms (Figure 3) allow urban residents to grow fresh produce near their houses. This not only results in savings in transportation costs as well as resource consumption but also supports urban greening. Further, hydroponics is being researched in the field of space exploration, as NASA has demonstrated with their research in micro-gravity food development. Hydroponic systems have been tested on the International Space Station (ISS) and have demonstrated that crops can be successfully grown in space. This book is gold for the long-duration spaceflights of the future, where mission success and crew health will depend on sustainable food production. Space-borne fresh food production potential could minimize reliance on pre-prepared food and provide astronauts with necessary nutrients for long-duration missions.

Lastly, hydroponics can offer a remedy for conventional agriculture, bypassing the limitations of water shortage, soil loss, and food shortages. Its innovative approaches, advantages of high returns and climatic control, and successful application in various environments make it a key part of the future of sustainable farming. The various hydroponic systems, along with their relative strengths and weaknesses, are provided in Table 2.

Figure 3. Vertical farming (Wadood *et al.*,2024

Table 2. Comparison of various hydroponic systems

Hydroponic System	Advantages	Disadvantages	Applications	Maintenance	Cost
Nutrient Film Technique (NFT)	Efficient use of nutrients and water; roots exposed to oxygen-rich environment.	Prone to system failure (e.g., power outage); susceptible to root diseases due to standing water.	Ideal for fast - growing leafy greens like lettuce, spinach, herbs.	Requires regular nutrient solution checks and maintenance of pumps.	Moderate
	Simple setup;		Suitable for	Low-maintenance,	

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Deep Water Culture (DWC)	constant supply of oxygen, water, and nutrients to roots.	Requires aeration for oxygen; risk of root rot in stagnant water.	larger plants like tomatoes, peppers, and cucumbers.	but regular cleaning of reservoirs is needed.	Low
Aeroponics	High oxygenation levels lead to faster growth; efficient nutrient usage.	High initial setup cost; sensitive to system failures like pump malfunctions leading to plant death.	Suitable for high-value crops and research applications, like strawberries and potatoes.	Requires monitoring of misters and nutrient solutions.	High
Wick System	Simple, passive system with no moving parts; low cost.	Limited to small plants; slow growth due to low nutrient availability.	Best for small herbs and low-maintenance plants.	Minimal maintenance, ideal for beginners.	Very Low
Ebb and Flow (Flood and Drain)	Provides intermittent exposure to nutrients, ensuring oxygen-rich root environment.	Potential pump failure; over or under-flooding may damage plant roots.	Common for a wide variety of crops, including flowers, herbs, and vegetables.	Regular monitoring of water levels, nutrients, and pump performance.	Moderate
Drip System	Precise control over nutrient and water supply to individual plants.	Emitters can clog easily; requires maintenance of drip lines.	Widely used for larger plants like tomatoes, peppers, and cucumbers.	Frequent emitter cleaning and system checks required.	Moderate to High
Kratky Method	Extremely simple, no electricity or pumps required; minimal intervention needed.	Limited to small-scale farming; water and nutrient levels must be monitored manually.	Suitable for leafy greens in home gardening setups.	Very low maintenance once set up.	Very Low

4. Automation in hydroponic systems

Hydroponics is just one of the several aspects of farming that have been revolutionized by the advent of technology. With hydroponic systems increasingly becoming popular, automation is becoming increasingly necessary in a bid to enhance sustainability, production, and efficiency. This section analyses the numerous elements that are required to maximize hydroponic farming activities, touches on the current level of automation of hydroponic systems, and highlights the imperative need for more automation.

4.1 Current state of automation

Many hydroponic systems are already available for a variety of crops, such as succulent plants, leafy greens, and herbs. However, most current hydroponic systems only exhibit a small degree of automation. For many systems, manual intervention is necessary for tasks like pH correction, nutrient mixing, and environmental parameter monitoring. Complete automation is not yet widely employed, but some commercial hydroponic devices contain timers for lighting and automation for fertilizer delivery.

Mechanized hydroponic systems like the Deep Water Culture (Figure 4) and Nutrient Film Technique (NFT) have been invented to allow crops to grow in wide range with minimal physical labor. Yet, some aspects like adjusting nutrients and troubleshooting need human input from these machines. Therefore, there is a big difference between the ideal fully automated hydroponic system that can control every element of plant growth without the need for human involvement and the technologies that are currently available. Table 3 lists the variables that affect seed germination.

Figure 4. Deep water culture (Wadood *et al.*, 2024)

Table 3. Factors affecting seed germination

Factor	Description	Impact on germination
Water (Moisture)	Water is essential for activating enzymes that break down stored food in the seed for growth.	Adequate water promotes germination, while waterlogging or drought conditions can inhibit the process.
Temperature	The optimal temperature range is crucial for enzyme activity and metabolic processes in seeds.	Too low or too high temperatures slow down or completely halt germination.
Oxygen (Aeration)	Seeds need oxygen for respiration during germination to convert stored energy into growth.	Poor aeration or compact soil restricts oxygen supply, negatively impacting germination rates.
Light (Photoperiodism)	Some seeds require light to germinate, while others may need darkness.	Depending on the species, light can either promote or inhibit germination (e.g., lettuce needs light).
Seed depth	The depth at which seeds are planted affects their access to water, oxygen, and light.	Seeds planted too deep may not have enough energy to reach the surface; shallow planting can expose seeds.
Soil pH	Soil pH affects nutrient availability and microbial activity around the seed.	Extreme pH levels can reduce germination by altering enzyme activity and nutrient availability.
Seed viability	The genetic and physiological state of the seed, often influenced by age and storage conditions.	Non-viable or old seeds are less likely to germinate, while fresh, healthy seeds have higher germination rates.
Salinity	High salt concentrations in the soil can affect the osmotic balance, hindering water uptake by seeds.	High salinity levels lead to reduced germination due to osmotic stress and toxicity.
Seed dormancy	Some seeds have natural dormancy mechanisms that must be broken before germination.	Dormancy may require specific conditions like stratification (cold treatment) to trigger germination.
Seed coat	The hardness or permeability of the seed coat can affect the seed's ability to absorb water and oxygen.	Thick or impermeable seed coats may require scarification (mechanical or chemical) to promote germination.
Nutrient availability	Access to essential nutrients in the growing medium can support early seedling development post-germination.	While seeds can germinate without external nutrients, poor availability can slow down seedling growth.

4.2 Automation needs

Automation requirements for hydroponic systems are multifaceted and encompass various issues of the primary concern that directly impact plant health and growth.

4.2.1 Controlling pH, light intensity, water circulation, and oxygen levels

Real-time pH monitoring and management is one of the most basic requirements for hydroponic system automation. The ideal pH level is crucial for nutrient absorption, and any divergence from this will affect growth in a harmful way. Autonomous systems can employ sensors to continuously measure pH and add pH-up or pH-down as needed (Lundin *et al.*, 2017).

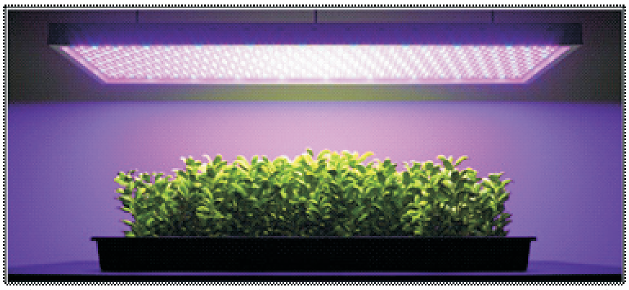

Figure 5. Light intensity control (Wadood *et al.,* 2024)

Light intensity control (Figure 5) is yet another vital automation factor. Crops require specific amounts of light to undergo photosynthesis, and automated lighting can vary light intensity and light duration depending on plant need and crop stage. LEDs can be programmed to provide the exact wavelengths needed for specific crops to thrive and produce optimally.

In addition, water circulation and oxygenation must be extremely well controlled. Automation can ensure effective water circulation in the hydroponic system and adequate oxygenation. Submersible pumps and air stones that create bubbles in the nutrient solution can be used to facilitate this, promoting oxygen uptake by the plants' roots (Campoy and Hernández, 2015).

4.2.2 Nutrient regulation and feedback systems

Hydroponics requires nutrition management because plants receive all of their nutrients from the nutrient solution. Computerized systems of nutrient delivery can offer the right amounts of macro-nutrients and micro-nutrients based on feedback from sensors measuring the electrical conductivity (EC) and total dissolved solids (TDS) in solution in real time.

Having feedback systems (Figure 6) can enhance nutrient management by monitoring plant health and adjusting the nutrient solutions accordingly. More advanced automation systems can take the readings from a range of sensors to inform them when to provide nutrients in order to maintain optimal growth concentrations for each crop type. This degree of precision in nutrient management not only promotes the greatest development but also lowers the waste, advancing the technique towards environmental sensitivity

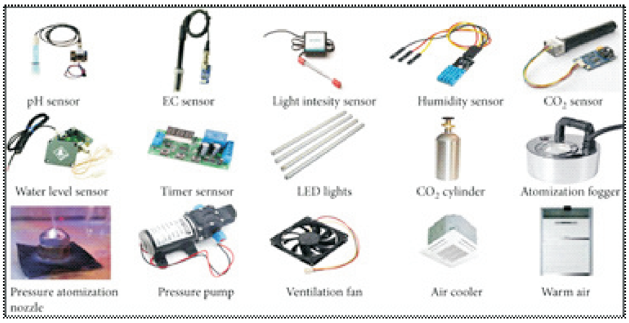

Figure 6. Sensors and actuators used in hydroponic system *(*Atmaja and Surantha, 2022)

4.2.3 Temperature control for killing microorganisms

Temperature is highly crucial in hydroponics, as elevated temperatures result in the multiplication of pathogens and disease-causing microorganisms. Heating and cooling units can be mechanized to provide optimal temperatures in the hydroponic system. For instance, heating mats may be employed to provide warm temperatures during the winter season, whereas fans or misting systems may be employed to lower temperatures during summer heat (Soussi *et al.*, 2022).

To keep the atmosphere in the best possible circumstances for plant growth and to prevent the spread of disease, thermostats and temperature sensors can also be added to the system so that heating and cooling can be automatically adjusted based on actual conditions (Juroszek and Tiedemann, 2011).

4.2.4 Irrigation control and water usage optimization

Proper irrigation management is another area where automation can play a significant role in hydroponic systems. Water utilization can be optimized using automated irrigation systems (Figure 7), which track evaporation levels and modify the water delivery as necessary. Soil moisture sensors or atmospheric humidity sensors can provide input to irrigation programs, ensuring plants receive adequate water without over-irrigation (Henderson *et al.*, 2018).

Drip irrigation and subsurface irrigation systems can also transport water to the plant roots, increasing efficiency even more. In addition to saving water, this also reduces the incidence of fungal diseases that are usually linked to damp conditions. Producers can evaluate their rates of consumption and make well-informed decisions to increase efficiency by automating the tracking of water consumption. Table 4 lists the variables influencing seed germination along with the technologies that are now accessible.

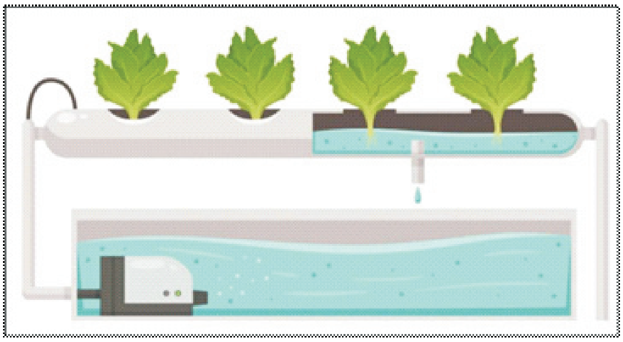

Figure 7. Re-circulation of water (Pomoni *et al.*, 2023)

Table 4. Factors affecting seed germination and available technologies

Factors	Description	Impact on germination	Available technology	Applications
Water (Moisture)	Water is essential for activating enzymes that break down stored food in the seed for growth.	Adequate water promotes germination, while waterlogging or drought conditions can inhibit the process.	Drip irrigation, Moisture sensors, Smart irrigation systems	Used in precision agriculture to ensure optimal water supply for crops.
Temp.	The optimal temperature range is crucial for enzyme activity and metabolic processes in seeds.	Too low or too high temperatures slow down or completely halt germination.	Temperature-controlled germination chambers, Soil temperature sensors	Greenhouses and controlled environments for better germination.
Oxygen (Aeration)	Seeds need oxygen for respiration during germination to convert stored energy into growth.	Poor aeration or compact soil restricts oxygen supply, negatively impacting germination rates.	Aerated seed trays, Perforated seedbeds, Substrate with high porosity	Used for optimal seedbed conditions, especially in commercial farming.

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Light	Some seeds require light to germinate, while others may need darkness.	Depending on the species, light can either promote or inhibit germination (e.g., lettuce needs light).	LED grow lights, Automated shading systems	Common in horticulture and vertical farming for light-sensitive crops.
Seed depth	The depth at which seeds are planted affects their access to water, oxygen, and light.	Seeds planted too deep may not have enough energy to reach the surface; shallow planting can expose seeds.	Precision seeders, Automated planting equipment	Used in large -scale agriculture to ensure optimal seed depth for various crops.
Soil pH	Soil pH affects nutrient availability and microbial activity around the seed.	Extreme pH levels can reduce germination by altering enzyme activity and nutrient availability.	pH meters, Soil amendments like lime or sulfur to adjust pH levels	Applied in agriculture to modify soil conditions for better crop germination and growth.
Seed viability	The genetic and physiological state of the seed, often influenced by age and storage conditions.	Non-viable or old seeds are less likely to germinate, while fresh, healthy seeds have higher germination rates.	Seed viability testers, X-ray imaging of seeds	Used in seed quality assurance processes in agriculture and seed banks.
Salinity	High salt concentrations in the soil can affect the osmotic balance, hindering water uptake by seeds.	High salinity levels lead to reduced germination due to osmotic stress and toxicity.	Soil salinity sensors, Desalinization techniques for irrigation water	Used in areas with high saline soil or water, like coastal and arid regions.
Seed dormancy	Some seeds have natural dormancy mechanisms that must be broken before germination.	Dormancy may require specific conditions like stratification (cold treatment) to trigger germination.	Stratification chambers, Chemical treatments (gibberellins)	Applied in horticulture and forestry for species with dormancy traits (e.g., fruit trees, timber).
Seed coat	The hardness or permeability of the seed coat can affect the seed's ability to absorb water and oxygen.	Thick or impermeable seed coats may require scarification (mechanical or chemical) to promote germination.	Mechanical scarification devices, Chemical treatments (sulfuric acid, hot water)	Used in forestry and certain crop species where seeds have tough coats (e.g., legumes).
Nutrient availability	Access to essential nutrients in the growing medium can support early seedling development post - germination.	While seeds can germinate without external nutrients, poor availability can slow down seedling growth.	Fertigation systems, Controlled-release fertilizers	Used in both soil - based and hydroponic systems to ensure early plant growth.

5. Partially automated systems and the need for improved automation in hydroponics

The incorporation of automation in hydroponic production has been a rising trend, and many case studies have considered the advantage of automating specific features of these systems. Still, the majority of the systems researched are at best partially automated, and there are particularly large gaps for fully automated hydroponic systems. In this section, various studies on partially automated hydroponic systems are discussed, and high-quality automation is highlighted to maximize crop production, lower labour costs, and increase resource efficiency.

5.1 Case studies

5.1.1 Automation in nutrient delivery systems

Diego *et al.* (2012) studied a partially automated nutrient delivery system employed in a hydroponic lettuce production facility. The system controlled the pH and electrical conductivity (EC) of the nutrient solution and adjusted nutrient concentrations automatically (Figure 8) using sensor feedback. While the system was effective at providing optimal levels of nutrients and minimized manual work by 40%, it was not adaptive to specific plant nutrient requirements during various growth periods. This research brings to the limelight a lack of real-time, adaptive regulation of nutrients that can be rectified through more sophisticated automation technology (Zhang *et al.*, 2020).

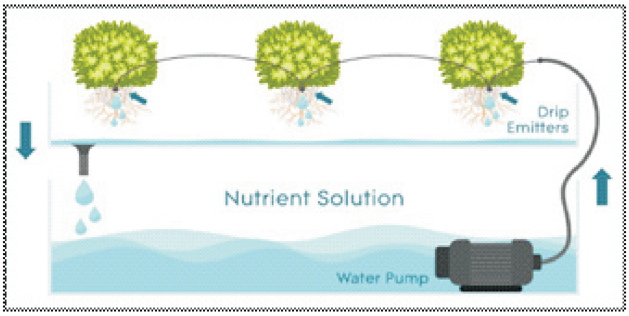

Figure 8. Nutrient delivery system (DelaVega *et al.*, 2021)

5.1.2 Automated environmental control systems

Azmi *et al.* (2024) tested a partially automated environmental control system in a small-scale urban hydroponic strawberry farm. Environmental controls were automated for temperature and humidity, but lighting and CO_2 levels were manually controlled by the operators (Domingues *et al.*, 2012). The study proved that automating the environmental controls resulted in increased crop yield by 25% due to the continuous control of ideal growing conditions. Nonetheless, manual management of lighting and CO_2 levels brought inconsistencies to the overall growth of the plants. The authors proposed that the incorporation of sensors for real-time observation of photosynthesis could automate the controls and enhance yield further (Langenfeld *et al.*, 2022).

5.1.3 Water usage optimization in semi-automated systems

Solis *et al.* (2022) performed a study of water consumption in a semi-automated hydroponic system intended for tomato production. The system used sensors to detect soil moisture and water levels (Figure 9), irrigating only when needed, cutting down on water wastage by 30%. Even with the water efficiency gain, the system was not integrated with evapotranspiration sensors (ET107), which would have enabled more accurate water delivery according to the requirements of the plants and conditions in the environment. The scientists claimed that automating the water delivery system completely with real-time evapotranspiration information would have led to even greater water-use efficiency.

Figure 9. Water usage optimisation in hydroponic system (Heins, 2024)

5.1.4 Remote monitoring and feedback systems

Paul *et al.* (2022) reported a study on a partially automated hydroponic system in India based on remote monitoring and feedback technologies. The farmers could observe environmental conditions, including temperature and humidity, through a mobile application. Nonetheless, the feedback system had to be intervened upon manually to control nutrient supply and environmental conditions. The study revealed that although remote monitoring was convenient, the absence of full automation caused delays in making important adjustments, lowering yield by 15% compared to fully automated systems. The study emphasized the necessity for feedback systems that would automatically control conditions using real-time sensor data.

5.1.5 Automation in pest and disease control

A semi-automated pest and disease control system was experimented with in a hydroponic system for leafy greens in a study conducted by Nikolov *et al.* (2023). The system utilized environmental sensors to check for conditions favourable for pests and released pest control agents, including foggers and UV lights. Although the system was effective in reducing the number of pests by 50%, it was less sensitive to dynamic changes because it was predicated on predetermined environmental limits. According to the scientists, using machine learning algorithms might improve the system's ability to predict insect outbreaks and enable proactive control.

6. Recent developments in hydroponics

Soilless plant cultivation, or hydroponics, has changed significantly over the past few decades through the introduction of new technologies and new forms of agriculture. These technology breakthroughs have provided for new potential in productive growth, tight control of the environment, and maximum resource optimization. This section gives a detailed description of advanced technological developments in hydroponics.

6.1 Domotics for indoor cultivation – Control tools

Domotics, or home automation systems, have played a key role in the development of indoor cultivation methods.Optimal growing conditions can be provided by centrally controlling the climate, lighting, humidity, and nutrient solution using domotics.Domotics-controlled climate management for indoor hydroponic systems reduced water use by 40% and enhanced crop yields by 25%, according to a study by Kaur *et al.* (2023). The technologies give farmers real-time information on the health and nutrient status of their plants and allow them to regulate conditions through smartphone applications. Likewise, Lutai and Kvachov (2020) explained how domotics' automation units can control light intensity and photoperiods, with the former being a requirement for optimizing hydroponic plant photosynthesis.

6.2 Data acquisition for cultivation

Modern hydroponics depends more and more on sophisticated data collection tools that monitor temperature, electrical conductivity (EC), pH, and fertilizer availability. Real-time data reading by these sensors provides input on the ideal circumstances required by different plant species. Real-time nutrient content monitoring improves fertilizer application efficiency and reduces environmental damage, according to Swathy *et al.* (2024). Additionally, Dhal *et al.* (2022) showed how adding machine learning algorithms and data collecting systems improved the formulation of nutrient solutions, which in turn increased yield and improved the quality of output.

6.3 Remote cultivation

The grower can remotely inspect and manage crops by combining hydroponic systems with remote monitoring tools. This aspect is considered to be helpful in commercial agriculture and urban locations where vertical farming is practised. Smartphone apps and cloud-based platforms help farmers in remotely controlling the environment, checking crop health in real time, and even modifying the amount of fertilizer. In a case study by Englar *et al.* (2021), a vertical farm unit in Tokyo used remote farming technology to reduce labour expenses by 15% and enhance production by 30%. In addition to that, remote monitoring allows plant diseases and nutrient deficiencies to be detected at an early point.

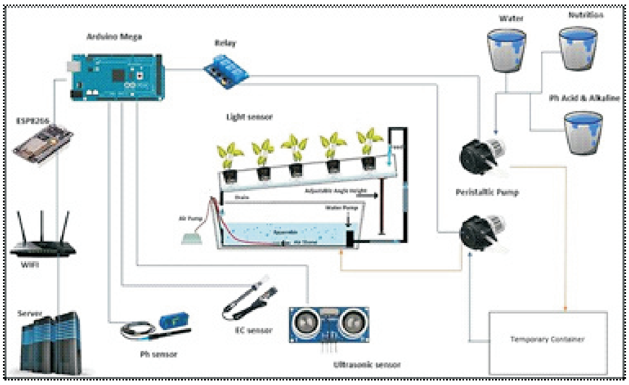

Figure 10. Hydroponic system integrated with IoT (Lakhiar *et al.*, 2018)

6.4 Integration of IoT in vertical farming

The Internet of Things (IoT) transformed vertical farming by providing various sensors and devices to communicate with one another, forming a complete automated system. IoT tools such as temperature sensors, humidity management systems, and nutrient delivery systems offer optimal growing conditions to the plants at all times. Rathor *et al.* (2024) showed that IoT-enabled vertical hydroponic systems (Figure 10) could reduce resource use by as much as 60% when compared to traditional farming. And also explained about the intelligent monitoring of plant growth and temperature changes is made easier by IoT integration, which enhances decision-making and resource allocation.

6.5 Aeroponics technology

Aeroponics (Figure 11), a hydroponics offshoot, is the cultivation of plants in an air or aerosol environment without soil or aggregate media. It has become popular because it can supply nutrients directly to roots using mist and can maximize nutrient uptake and stimulate quicker growth. Lakhiar *et al.* (2018) assert that aeroponic systems have 45% more plant growth as compared to traditional hydroponic systems because there is improved oxygenation of the root zone. Furthermore, Gopinath *et al.* (2017) determined that aeroponics is especially well-adapted to high-value crops like leafy greens and herbs where accuracy of nutrient delivery is paramount.

Figure 11. Aeroponic system (Wadood, 2024)

6.6 AI-Driven Hydroponics

Artificial intelligence (AI) has been an influential agent in hydroponic agriculture, allowing predictive modelling, self-decision-making, and optimization of the growing environment. AI algorithms are able to observe large quantities of data gathered from sensors and forecast the best possible growing conditions. For instance, Satpute and Singh (2024) illustrated that AI-based systems can lower water and nutrient losses by 25% along with an increase in crop yields by 30% in a laboratory hydroponic setup. AI is also utilized to predict plant diseases as well as maximize resource utilization with the help of real-time information.

6.7 Agro-technology and automation

Hydroponics has been made more automated through robotisation, from seed and transplanting to harvesting and packaging. With automation, work that was originally done manually can be done automatically, hence saving labour costs and increasing efficiency. Saad *et al.* (2021) examined automation effects in big hydroponic farms in the Netherlands, displaying that farms equipped with automated harvesting systems had their labour costs decrease by 40% and productivity increase by 20%. Automation also provides greater control over the growth cycle so that quality is consistent in all crops.

6.8 Hydroponics in hospitals

Hydroponic systems are increasingly being employed in hospitals to supply fresh, nutritious produce to patients so that they recover faster and enjoy good health overall. In India, Khan *et al.* (2020) documented the utilization of hydroponic systems in hospital kitchens to grow organic vegetables for patients who have chronic diseases. According to the study, hydroponics provided fresh, pesticide-free veggies while reducing the hospital's dependency on outside food sources by 50%. Hydroponics is also being investigated by hospitals for therapeutic uses, in which patients take part in the growing process as a component of their recovery.

6.9 Efficient resource utilization

By its very nature, hydroponic farming requires fewer resources than traditional farming methods. The environmental effect of closed-loop hydroponic systems is significantly reduced by permitting the recycling of water and nutrients. Water-scarce areas like Gujarat and Rajasthan in India are perfect for hydroponics because it needs 90% less water than soil agriculture (Khan, 2018). Additionally, Magwaza *et al*. (2020) showed that hydroponics might be highly effective in urban environments with limited space and resources.

7. Practical application of hydroponics by automated system

With the use of nutrient solutions in water, hydroponic systems have transformed contemporary farming by facilitating the cultivation of plants in the absence of soil. Such systems are presently more efficient due to automation, which has enhanced growth conditions and yields. Automated hydroponic systems employ technology to monitor and control environmental parameters, subjecting conditions to ideal for plant development. Through the use of control systems and sensors, such systems realize precise measurements of humidity, temperature, light, and nutrient concentration, thereby reducing human error and involvement. This automation results in uniform and improved crop yields. Relative humidity is important in plant transpiration and nutrient uptake. Automated systems are constantly monitoring and maintaining humidity levels to avoid problems like mould formation or dryness (Anonymous, 2022). The temperature of the water is also an important consideration since it allows for the uptake of nutrients and root health. Automated systems control the temperature of the water within the preferred range, leading to healthy plant growth (Anonymous, 2017).

Research has proven that the automation of hydroponic systems increased crop yield by a great margin. The comparative growth of tomato and lettuce under indoor automated and outdoor manual hydroponic systems showed large differences in plant growth. Compared to outside plants, which grew to a height of 17.31 cm and 8.71 cm, respectively, indoor plants grew to a height of 27.89 cm for tomatoes and 27.38 cm for lettuce. The indoor system generally had wider and longer leaves; indoor lettuce had the widest leaves (3.94 cm), whereas indoor tomatoes had the widest leaves (1.14 cm). Leaf formation was considerably lower in outdoor lettuce (10.6) and significantly higher in indoor tomato (57.1 leaves), suggesting that controlled environmental conditions were advantageous for leaf formation. SPAD readings of indoor tomato (30.08) were highest, and that of outdoor lettuce (16.51) was lowest, which supports the advantages of indoor farming in maximizing plant health. The results indicated the benefits of controlled environment agriculture with consistent conditions promoting better plant development and physiological performance than conventional outdoor agriculture (Rathnayake *et al.*, 2023).

There have been numerous case studies investigating the advantages of automated hydroponics. Monitoring systems based on IoT have been seen to enhance resource utilization and crop yields through real-time monitoring and maintenance (Shahaand Budhathoki, 2024). Sensor integration has permitted better diagnostics and optimization of growth conditions, leading to increased plant health and productivity (Anonymous, 2017). Automated environmental control systems have generated perfect growing conditions, boosting yields and lowering disease risk (Anonymous, 2022). Methods like deep water culture have been successfully coupled with automation to encourage fast growing of plants and increased yields (Resh, 2022). Nutrient film technique, which employs a thin layer of nutrient solution over roots, has also been maximized with automated systems to increase yield and decrease water use (Albright *et al.*, 2000). Controlled-environment agriculture, the integration of hydroponics and automation, has demonstrated great promise in urban agriculture applications (Graves, 2019).

6. Future scope

Though the case studies discussed above show the promise of partial automation in hydroponic systems, there are some critical gaps that should be worked on for better automation.

8.1 Real-time adaptive systems

Several of the existing systems are not fully adaptive. Sensors tend to initiate action based on pr-programmed thresholds, but nutrient, water, and environmental requirements of crops change through their growth cycle. Machine learning algorithms that can interpret plant growth data and forecast optimal cultivation conditions are necessary for completely adaptive systems.

8.2 Integrated multi-sensor systems

The majority of systems are based on separate sensors for each parameter, like temperature or pH. Combining several sensors that give an overall image of the plant's health and the surrounding environment will lead to more informed decisions. An example is the integration of nutrient sensors with photosynthetic activity sensors to optimize the delivery of nutrients in real-time.

8.3 Predictive analytics and AI integration

Many systems lack forecasting features that can predict plant needs depending on the growth patterns or environmental changes. Artificial intelligence models can predict nutrient needs, pest attacks, or optimal harvest periods using historical records, thus making operations more efficient and less dependent on interventions.

8.4 Remote automation and feedback systems

Whereas remote monitoring systems exist, the majority are still dependent on manual interventions. Fully automated feedback systems able to adjust levels of nutrients, water, or environmental conditions by themselves using real-time data to make remote cultivation more efficient are necessary.

8.5 Cost effective solutions for small-scale farmers

Most advanced automation techniques are expensive and out of reach for small-scale or resource-poor farmers, particularly in developing nations such as India. For more widespread adoption of hydroponics in countries such as India, cost-effective automation systems should be developed that can scale based on farm size and economic limitations.

In the aftermath of today's agricultural difficulties, especially with the population pressure growing rapidly and the amount of arable land decreasing, hydroponics became the necessary tool. The soilless plant-growing technique known as hydroponics maximises crop productivity because of regulated environmental conditions, reduces the influence of soil-borne illnesses, and makes optimum use of resources. The sustainable alternative of hydroponics offers the ability to produce high-quality crops in a variety of situations, as conventional farming is unable to meet the demands of food security. Incorporating automation technologies into hydroponics is critically vital to enhance accessibility and efficiency. Automation is in favour of precise control of various elements such as nutrient supply, pH, light, and temperature required to maximize plant growth. With the assistance of data acquisition devices and integration of IoT, hydroponic crops can operate independently with minimal human intervention, allowing for scalable systems that are deployable in urban and low-land agricultural areas. The establishment of automated systems not only reduces labour costs but also the quality and uniformity of the harvest, making hydroponics a viable alternative for commercial farmers.

Looking to the future, hydroponics has a huge potential to contribute to supporting the growing world population while also mitigating the challenge posed by adverse environments. Applications of hydroponics stretch beyond soil agriculture to endeavors in space exploration, where maximum production systems for food are crucial if successful long duration missions are to be achieved. Hydroponics can also prove to be a critical answer in deserts, where conventional agriculture is confronted with limited water and low-fertility land. As technology goes forward into the direction of automating and employing hydroponic methods, the future holds much promise for a sustainable future for agriculture that will be able to provide the required nutrition for an increasing population without wasting precious resources.

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