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THE PERSPECTIVES OF HYDROPONICS CULTIVATION SYSTEM: A REVIEW

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Abstract

Hydroponics is a growing technique that uses aqueous media (nutrient solution) to support plant growth. This technology offers viable solutions to today's global challenges. In the context of the decreasing and degrading of available agricultural land, hydroponic systems can contribute to food security. The main objective of this study is to analyze the current hydroponic techniques and nutrient solution management. Additionally, the study explores the groundbreaking advancements in hydroponic cultivation, emphasizing the integration of sensor-based monitoring systems and automated control technologies, which collectively enhance resource efficiency and optimize plant growth conditions while enabling precise, data-driven agricultural practices. The conclusions of the study emphasize that hydroponic agriculture is an alternative with high potential for increasing crop yields and optimizing the use of limited resources.

***Key words**: growing technique, nutrient solution, food security, smart farming.*

INTRODUCTION

The amount of land and water available for agricultural crops has decreased throughout centuries due to urbanization, population increase and soil degradation (Dobermann et al., 2013). According to estimates, half of the world's land will not be adequate for agriculture by 2050 (Olowe, 2021). The United Nations (UN) claims that there is a food crisis in several nations right now (Okemwa, 2015). As a result, contemporary methods for attaining sustainable agriculture have begun to attract interest (AlShrouf, 2017).

Climate change, more frequent floods and droughts, soil erosion and degradation from traditional farming practices that deplete the soil of vitamins and minerals are the main causes of this collapse. As a result, methods to enhance and boost agricultural systems' production must be developed and implemented globally (Gashgari et al., 2018).

Because there are a number of negative environmental repercussions associated with traditional agriculture methods, growing techniques that are soilless have gained popularity (Killebrew & Wolff, 2010; Walls, 2006).

The earliest published work on growing land plants without soil was found in the book *"Sylva Sylvarum"* by Francis Bacon in 1627 (Swain, 2021). The term "Soilless culture" mostly refers to hydroponic, aeroponic and aquaponic methods.

The term hydroponics was derived from the Greek words "hydro", meaning water and "ponos", meaning labor (Biebel, 1958).

The earliest records of hydroponics in use were in the Hanging Gardens of Babylon, where plants were grown in a continuous stream of water (Wahome, 2015).

Dr. Gericke, a professor from California, introduced the term "hydroponics" in 1929 as he started to transform a previously lab-based method into a commercial way of cultivating plants (Sardare & Admane, 2013). The phrase was still in use until the 1980s, although it became more inclusive (Ciofu, 2003).

According to some authors, hydroponics is a technique of growing plants in nutrient solutions (containing water with fertilizers) with or without the use of an inert medium (substrate: sand, gravel, vermiculite, rockwool, perlite, coconut fiber) to provide mechanical support (Sharma et al., 2018). In 1983, Collin and Jensen expanded the definition of "hydroponics" to encompass the entire spectrum of crops cultivated on both organic and mineral substrates (Ciofu, 2003; Draghici & Jerca, 2021).

Hydroponics is an excellent way for people who don't own land to grow plants as a hobby because it can be done in extremely small spaces, with little work and little time (Barman, 2016).

During World War II, the US military employed use hydroponics to produce fresh food for soldiers positioned on desolate Pacific islands. By the 1950s, there were successful commercial farms in Asia, Africa, Europe and the Americas (Sardare & Admane, 2013).

In Romania, the first experiments in the field of hydroponic crops on nutritive solutions were carried out by the researchers of the vegetable-growing section of the former Horticultural Research Institute in the 1960. In the late 1980s, at the Faculty of Horticulture in Cluj, an experimental program was started to develop unconventional technologies for the production of tomatoes and cucumbers in greenhouses. Also during that period, at the Bucharest-Berceni Greenhouse Complex, an area of 1 ha was set up and exploited for 2 years for the cultivation of tomatoes on mineral wool, fed with nutrient solution in an open circuit (Ciofu et al., 2003).

MATERIALS AND METHODS

This study primarily focuses on a comprehensive analysis of the resources accessible within the global body of scientific literature.

The Google Academic, Free Full PDF, Research Gate, Science Direct, MPDI, Frontiers, Web of Science, PubMed, and others easily accessible online resources provided the data for this investigation. To identify the content of our work, we searched for phrases and terms like "soilless cultures", "hydroponic growing techniques", "nutrient solutions" and "modern technics in hydroponics".

This document comprises exclusively credible research articles published in peer-reviewed scientific journals in recent years, presenting established advancements and future prospects for hydroponic growth systems.

In accordance with these standards, 114 studies were incorporated into the analysis, influencing the final amendment. Only studies that satisfied predefined criteria were considered.

RESULTS AND DISCUSSIONS

Vegetables including tomatoes, lettuce greens, cucumbers and peppers, as well as decorative crops like herbs, roses, freesias and foliage plants, can be produced using hydroponics (Sardare & Admane, 2013).

The main crops suitable for hydroponic cultivation are systematically presented in Table 1.

Table 1. Crops suitable for hydroponically growing

Type of culture	Crop name
Cereals	*Oryza sativa* (rice), *Zea mays* (corn)
Fruits	*Fragaria ananassa* (strowberies)
Vegetables	*Lycopersicon esculentum* (tomatoes), *Capsicum frutescens* (chili pepers), *Solanum melongena* (eggplant), *Phaseolus vulgaris* (green bean), *Beta vulgaris* (sugar beet), *Psophocarpus tetragonolobus* (peas asparagus), *Capsicum annum* (pepper), *Brassica oleracea var. capitata* (cabbage), *Brassica oleracea* var. *botrytis* (cauliflower), *Cucumis sativus* (cucumber), *Cucumis melo* (melon), *Raphanus sativus* (wrinkles), *Allium cepa* (onion)
Leafy vegetables	*Lactuca sativa* (salad), *Ipomoea aquatica* (spinach)
Spices	*Petroselinum crispum* (parsley), *Mentha spicata* (ment), *Ocimum basilicum* (basil), *Origanum vulgare* (oregano)
Ornamental flowers-crops	*Tagetes patula* (tagetes), *Rosa berberifolia* (roses), *Dianthus caryophyllus* (carnation), *Chrysanthemum indicum* (chrysanthemum)
Medicinal crops	*Aloe vera* (aloe), *Solenostemon scutellarioides* (Coleus)
Forage crops	*Sorghum bicolor* (sorghum), *Medicago sativa* (lucerne), *Hordeum vulgare* (barley), *Cynodon dactylon* (pir gros), *Axonopus compressus* (Carpet grass)

In contemporary agriculture, hydroponic cultivation represents one of the most advanced and intensive crop production methodologies (Swain, 2021). These systems are a viable agricultural alternative for non-fertile or metal-contaminated soil (Supraja et al., 2020) and have a quicker growth rate (30-50%) Huo, 2020.

Hydroponic technology allows optimal utilization of nutrient solutions, water and space, as well as better control of climate and plant protective factors. Hydroponic technology can be an effective means for food production in ecosystems and extreme environments, such as deserts, mountainous regions, or arctic communities (Gaikwad & Maitra, 2020). For instance, people living in underdeveloped and poor regions of Thailand cannot grow enough food using traditional agricultural practices due to high soil salinity and lack of natural nutrients in the soil, but hydroponic systems can successfully generate additional crop yields (Ortiz et al., 2009).

Growing in popularity around the world, hydroponic systems provide growers and consumers with a variety of new chances to produce high-quality harvests, such as vegetables improved with bioactive substances (Jan et al., 2020).

Europe is recognized as the predominant hub of the hydroponics market, with France, the Netherlands, and Spain emerging as the leading producers, followed by the United States and the Asia-Pacific region (Prakash et al., 2020).

Hasan et al. (2018) stated that hydroponic systems frequently necessitate specialized infrastructures and a controlled microclimate, which can be regulated within protected cultivation environments.

Hydroponic crop classification is primarily determined by factors such as drainage systems, substrate and container types, as well as the nutrient delivery mechanisms employed (Hasan, 2018).

There are a number of different systems and techniques used that fall under the category of 'hydroponics'. According to some authors, hydroponic techniques have been divided into two categories, as presented in Table 2: growing in solution and growing in solid media (growing media) (Atherton & Li, 2023).

Tabel 2. Classification of hydroponic tehniques

Culture in nutrient solution		**Culture in solid media**
Non-circulating systems (open system)	**Circulating systems (closed system)**	
Root-sinking technique	Nutrient film technique (NFT)	Hanging bag technique
Floating technique	Deep flow technique (DFT)	Grow bag technique
Capillary action technique	Drip technique	Pot technique
	Wick technique	Trench/trough technique
	Flood and flow technique	

1. Solution culture: plant roots are placed directly in liquid (nutrient solution). Solution culture can be subdivided into circulating and non-circulating systems (Atherton & Li, 2023).

A. Non-circulating systems (open system) in which excess nutrient solution not utilized by plants is discharged to the environment (Ciofu et al., 2003).

- *Root submersion technique*: plants are suspended above the nutrient solution, with their roots partially immersed in the solution to a depth of approximately 2-3 cm (Atherton & Li, 2023).
- *Floating technique:* the plants are affixed to a lightweight polystyrene plate, which floats atop the nutrient solution, ensuring that the roots remain fully submerged within the solution (Hussain et al., 2014).
- *Capillary action technique:* pots filled with an inert medium feature perforations at the base and are positioned in shallow containers that hold the nutrient solution (Hussain et al., 2014). The nutrient solution reaches the plant roots by capillary action. The technique is suitable for ornamentals, flowers and indoor plants (Swain et al., 2021).

B. Circulating systems (closed system): in which the nutrient solution is collected, reconditioned and recirculated to the growing facilities (Ciofu et al., 2003; Draghici & Jerca, 2021).

- *Nutrient Film Technique* (NFT): NFT was developed in the mid-1960s in England by Dr. Alen Cooper to overcome the shortcomings of ebb and flow systems. The nutrient film technique (NFT) is the most popular hydroponic system. In this method, the plants are placed in a polyethylene tube that has slits cut for the roots to be inserted (Shrestha & Dunn, 2010). The nutrient solution is constantly pumped through the tube in which the plants are placed (Ciofu et al., 2003).
- *Deep flow culture* (DWC): This method involves suspending plant roots in nutrient-rich water. Because algae and molds can grow quickly in the reservoir, it is essential to closely monitor the oxygen and nutrient concentrations, pH and salinity. This approach can be used to cultivate vegetables like tomatoes and cucumbers with great success (Swain et al., 2021).

- *Drip technique:* a drip emitter is used to periodically supply the nutrient solution to a substrate that has plant roots on it (Fussy & Papenbrock, 2022). By using nozzles, the drip emitter slowly disperses nutrients and extra solutions can be gathered and recycled or simply let run off. With this technique it is feasible to cultivate multiple plant species at the same time (Jan et al., 2020).
- *The wick technique*: is the simpliest hydroponic system that doesn't need aerators, pumps or power (Swain et al., 2021). Plants are submerged in an absorbent medium, such as perlite, vermiculite, etc., that transfers from the roots of the plants into a nutrient solution reservoir. Capillary action is how plants get their nourishment (Fussy & Papenbrock, 2022). Small plants, herbs and condiments respond well to this approach (Jan et al., 2020).
- *Flood and drain technique:* this is the first commercial hydroponic system. This system uses a growing tray and a reservoir that is filled with a nutrient solution. A pump periodically floods the growing tray with nutrient solution, which is then slowly drained. It is possible to grow different types of plants, but careful attention must be paid to the problem of root rot, algae and mold; therefore, a system with modified filtration is required (Jan et al., 2020).

2. Development on solid medium (in growth media): This approach contrasts with direct solution-based cultivation, as the plants are fully supported by a solid substrate. Fertigation is employed to deliver the nutrient solution either on top of or beneath the substrate surface (Atherton & Li, 2023).

Numerous research studies have been conducted in the research greenhouse of the Research Center for the Study of Agro-Food Product Quality within the University of Agronomic Sciences and Veterinary Medicine of Bucharest, from 2014 to the present. These studies have focused on optimizing tomato cultivation technologies on nutrient substrates, with particular emphasis on the use of perlite as a growing medium (Drăghici et al., 2021; Stoica et al., 2021; Stoica et al., 2022).
- *Hanging bag technique:* this method entails suspending polyethylene bags, approximately one meter in length and filled with a culture medium, over a gutter or channel. Plants are placed in mesh pots positioned within holes cut into the sides of the bags. The nutrient solution is pumped from a reservoir to the top of the bags, where it percolates through the culture medium, drains into the gutter, and is subsequently recirculated back into the reservoir (Waiba et al., 2020).
- *Grow bag technique:* growth media-filled polyethylene bags are set on the ground. Seedlings or seeds are inserted into the bag after tiny holes have been made in it. After that, each plant receives a nutrient solution via pipes (Sengupta & Banerjee, 2012).
- *Potting technique:* is similar to the growing bag technique, except that plants are placed in individual pots filled with culture medium and individually fertigated (Hasan et al., 2018).
- *Trench/trough technique:* trenches or troughs created above the soil are lined with an impermeable material and filled with inert medium. Plants are then placed in the trough at intervals and are supplied with nutrient solution by drip irrigation (Fussy & Papenbrock, 2022). Sometimes, a drainage pipe is placed at the bottom to allow excess solution to drain into the soil (Waiba et al., 2020).

Management of nutrient solutions used in hydroponics

When discussing hydroponic growth systems, the nutrient solution is the most important determinant of crop quality (Asao, 2012). For hydroponic crops, nutrient solution is a significant and necessary supply of nutrients (Patil et al., 2020).

According to Steiner (1961), the nutrient solution utilized in hydroponic systems is an aqueous solution mostly composed of soluble salts of inorganic ions of the elements necessary for plants. Iron chelates and other chemical compounds can occasionally be found as well (Suazo-López et al., 2014).

Trejo-Téllez et al. (2007) noted that elements such as sodium, silicon, vanadium, selenium, cobalt, aluminium, and iodine are regarded as beneficial due to their ability to stimulate plant growth. These elements may mitigate the toxic effects of other substances or serve as substitutes for essential nutrients in a less specific capacity.

Nutrient solutions, which form the foundation of hydroponic systems, primarily consist of macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur), with additional supplementation of micronutrients (Patil et al., 2020).

Electronic conductivity (EC), pH, concentration, temperature and nutrient solution formula are the main determinants of nutrient solution quality (Patil et al., 2020).

a. ***Nutrient solutions formula***

Proper nutrient solution formation and management are the keys to success for hydroponic crop production (Patil et al., 2020).

To facilitate the use of nutrient solution, there are a number of formulations available on the market to choose from. However, hydroponic growers can also prepare their own fertilizer mixtures to prepare nutrient solutions using fully water soluble nutrients. When preparing a nutrient solution, it is crucial to select fertilizers that are chemically compatible, as certain fertilizer salts may react adversely with one another. For instance, ammonium sulfate combined with potassium chloride results in the formation of less soluble potassium sulfate in the tank. Similarly, phosphate fertilizers can cause issues when present in high concentrations of calcium and magnesium, leading to the precipitation of poorly soluble phosphates (Kumari et al., 2018). Kong and Iersel (2004) reported significant increases in shoot growth, total dry weight, and leaf area in sage crops as the nutrient solution concentration was elevated from 0.125 to 1.0.

Nada et al. (2010) suggested that the critical boron concentration in nutrient solution is 4 ppm for long-term hydroponic tomato cultivation

De Bever et al. (2013) observed that the photosynthetic rate, evapotranspiration and intercellular CO2 concentration and chlorophyll content of *Beta vulgaris* (sugar beet) were generally higher in nutrient solution treated with nitrogen that was readily available to plants

Lopez-Pozos et al. (2011) found that inadequate oxygenation of nutrient solution (NS) in recirculated hydroponic systems leads to root hypoxia as a result of low oxygen solubility. Hypoxia affects crop nutrients and water uptake and results in reduced crop yield.

b. ***Electrical conductivity (EC) and pH of the nutrient solution***

It has been demonstrated that a culture can yield a diverse array of species by regulating the concentration of the nutrient solution, commonly referred to as electrical conductivity or osmotic pressure (Libya et al., 2012; Trejo-Téllez & Gómez-Merino, 2012; Kang & Van Iersel, 2009).

Sonneveld & Voogt (2009) reported that nutrient composition determines the electrical conductivity and osmotic potential of the solution. The ideal electrical conductivity (EC) is crop specific and dependent on the environmental conditions; however, values of electrical conductivity (EC) for hydroponic systems range from 1.5 to 2.5 ds m^{-1} (Sonneveld et al., 2009).

Samarakoon et al. (2006) found that higher electrical conductivity (EC) hinders nutrient uptake by increasing osmotic pressure, while lower electrical conductivity (EC) can severely affect plant health and yield (Samarakoon et al., 2006).

Low electrical conductivity implies a low nutrient concentration, which usually leads to nutrient deficiencies and slow plant growth rates; however, very high levels can burn and/or kill plants. Cuttings and tender plant seedlings can experience burns if the conductivity/ TDS is too high. Only after the plant begins to grow does it need a stronger nutrient solution. Some plants prefer milder nutrient strength, while other plants produce better-quality fruit with higher nutrient strength (Gaikwad & Maitra, 2020). Increased electrical conductivity in the nutrient solution tends to restrict the movement of calcium to developing fruit and increases the incidence of blossom end rot (BER), a physiological disorder that is associated with low calcium concentrations, especially at the distal end of the fruit (Adams & Ho, 1989).

When the nutrient solution is recycled, ions can accumulate, resulting in a significant increase in electrical conductivity (EC). This accumulation causes nutrient imbalances (depletion of some nutrients), affecting both yield and quality of the crop. The high concentration of sulfate in the nutrient solution reduces foliar Ca concentration and relative calcium activity but does not affect fruit yield or foliar content (Lopez et al., 2002).

Rafaela et al. (2017) revealed that the yield of the lettuce crop reduced considerably with increasing electrical conductivity and eventually osmotic pressure. The stress of saline exposure fundamentally interferes with plant functions such as photosynthesis and protein synthesis.

Saline stress inhibits plant growth by osmotic effect, restricting water availability and disturbing nutrition (Guimaraes et al., 2017).

The pH of the nutrient solution plays an important role in hydroponic cultivation. When the pH is not at the appropriate level, plants will lose their ability to absorb some of the essential elements needed for healthy growth. For all plants, there is a certain optimal pH level (Trejo-Téllez & Gómez-Merino, 2012). This pH level will vary from plant to plant; the recommended pH for hydroponic agriculture is between 5.5 and 6.5. This is because the overall availability of nutrients is optimized at a slightly acidic pH (Patil et al., 2020).

Ahn and Ikada (2004) found that the optimal pH is between 5 and 7, and the optimal concentration of the nutrient solution is ¼ to 1 unit of standard solution (Ahn & Ikeda, 2004).

Contamination control in hydroponic systems

In hydroponic cultures, maintaining a sterile environment in the root zone is essential for good plant vigor. The application of pesticides is generally avoided in hydroponic systems. With reduced pest problems and constant feeding of the roots with nutrients, productivity in hydroponics is high, despite limited plant growth due to low atmospheric carbon dioxide levels or limited light (Sardare & Admane, 2013).

However, although hydroponic cultivation is much easier to control in terms of contamination, this type of cultivation can still suffer. A disease commonly encountered in hydroponic cultivation is wilting, caused by *Fusarium* and *Verticillium* (Raviv et al., 1998). Only the thermal treatment of the nutrient solution was found effective in keeping the root zone free of pathogens (Savvas, 2002).

The advantages and disadvantages of hydroponics

There have been many questions regarding whether hydroponic crops are actually more efficient than soil-based crops. An experimental study conducted by Maeva Makendi showed a competitive analysis between growing plants hydroponically and growing plants in soil systems. The experiment was conducted on different types of plants over the course of a month. The hypothesis stated: "If hydroponic plants and soil-grown plants are given the same germination and growth conditions, then hydroponic plants will perform just as well, if not better, than soil-grown plants". It was concluded that hydroponic plants germinated and grew faster than soil-grown plants (Montgomery, 2017).

Thus, a comprehensive comparison between hydroponic systems and soil-based cultivation systems reveals numerous advantages (Savvas, 2002); however, soilless culture also presents certain limitations (Sonneveld, 2000). A thorough SWOT analysis of these systems, outlining both their strengths and weaknesses, is presented in Table 3.

Table 3. SWOT analysis of hydroponic system

Swat analysis

Key Components	Description	Literature
Strengths	Hydroponic systems produce the healthiest crops with high yields and are consistently reliable.	Silberbush & Ben-Asher, 2001
	Hydroponic system requires very little work and is very simple and clean.	Silberbush & Ben-Asher, 2001
	Considering that nutrients are delivered straight to the roots in hydroponic systems, plants develop more quickly and have fewer roots.	Silberbush & Ben-Asher, 2001
	Space is saved as only 1/5 of the total space is used.	Silberbush & Ben-Asher, 2001
	Since there is little chance of weed emergence, chemical treatments are not necessary.	Sonneveld, 2000
	Because hydroponic cultivation guarantees effective nutrient management, production per acre increases and product quality improves.	Sonneveld, 2000
	Work for various intercultural operations such as plowing, cultivating, watering and other practices is largely eliminated.	Swain et al., 2021

	This technique can use fertilizers and water effectively. Consequently, there is little possibility of losing valuable chemicals; it may result in less land pollution.	Swain et al., 2021
	The plants are grown locally, therefore the excess carbon can be reduced.	Swain et al., 2021
	Hydroponic growth also reduces soil problems, such as seed degradation, seedlings, and diseases related to soil-dwelling fungi.	Geilfus & Geilfus, 2019
Weaknesses	The application on a commercial scale requires technical knowledge and a large initial investment.	Sonneveld, 2000
	Hydroponics is limited to high-value crops given the high cost.	Swain et al., 2021
	Is needed a strong and unlimited source of electrical energy for the system.	Van Os et al., 2002
	Before starting the cultivation of any vegetable crop, proper training is an important prerequisite.	Swain et al., 2021
	It is very important to understand how plants grow and the principle of nutrition.	Swain et al., 2021
	The grower must observe the plants every day, as the plant's reaction to good or deficient nutrition is incredibly rapid.	Swain et al., 2021
	Cultivators must have knowledge of climate control within the structure.	Swain et al., 2021
	Crops grown in soil benefit from the mineralization of nutrients in the soil and microbial activity, whereas hydroponic plants rely exclusively on the addition of fertilizer to the nutrient solution.	Djidonou & Leskovar, 2019
	These systems have the disadvantage of requiring large inputs of water and fertilizers.	Kempen et al., 2017
Opportunities	In areas of the world where there is a shortage of arable or fertile land for agriculture, it works efficiently.	Sonneveld, 2000
	The maximum yield can be obtained by making the system economically feasible on high-density and expensive land.	Swain et al., 2021
	It is possible to produce vegetables 'out of season', thus providing an economic benefit to growers.	Swain et al., 2021
Threats	There is a chance of rapid spread of substrate-borne diseases and nematodes to all beds on the same nutrient reservoir of a closed system.	Swain et al., 2021

Smart hydroponic

Due to the fact that hydroponics creates an artificial growth environment, it requires automation technology to maintain and keep it within the correct range (Jain and Kaur, 2024).

Artificial intelligence-based systems and Internet of Things (IoT) automated growing procedures are two examples of innovative technologies that have lately gained popularity and have practical applications in indoor hydroponic operations (Javaid et al., 2020; Rajaseger et al., 2023). Smart agriculture relies on communication technologies and information for decision-making (Abd Ghani et al., 2023). Industry 4.0 and the application of technologies such as IoT, cloud computing, AI and ML (machine learning) to predict growth parameters for different plants (Mamledesai et al., 2020) can make hydroponics even more efficient (Ragaveena et al., 2021). Each plant requires a varied set of nutrients because they have varying pH and EC ranges for different growth phases. It is difficult for farmers to keep track of these and manually control everything (Shetty et al., 2021). As technology advances, the integration of smart technologies, automation and data analysis in hydroponics further enhances its potential. This integration allows for real-time monitoring, precise control and automation of various processes, leading to greater efficiency, reduced labor requirements and improved overall productivity (Resh, 2022).

IoT-assisted parameter control

In recent years, numerous efforts have been made to develop smart agricultural systems capable of monitoring and controlling various plant growth parameters, such as light intensity, temperature, resource usage, energy consumption, relative humidity, electrical conductivity, dissolved oxygen and pH (Gillani et al., 2022). The problem with hydroponic agriculture is the continuous requirement to maintain and control the artificial growth environment to allow optimal plant growth. The quality of the plants grown on the farm can be significantly affected by changes in climate, natural light and fertilizer solution at any time during the plant's growth cycle. According to studies, each increase of 3°C in the ambient temperature within the optimal range reduces crop productivity by 10% to 40%. Therefore, by automatically providing the ideal growth conditions throughout the growth cycle, IoT-based automation is crucial for achieving optimal plant growth (Jain and Kaur, 2024).

IoT can be defined as a vast network that allows the connection of any objects and people anytime and anywhere, using a service (Perera et al., 2014; Jin et al., 2014). In recent years, the number of devices encompassing the Internet of Things (IoT) has increased from 0.9 billion objects in 2008 to 50 billion by the end of 2020, making it a part of every existing application (Perera et al., 2014; Ghobaei-Arani et al., 2019; Kour et al., 2021; Chauhan et al., 2021). Sensors are the backbone of IoT networks and are an integral part of all IoT applications, including precision agriculture (Shieh et al., 2001; Antonacci et al., 2018). They are also used in various smart agriculture solutions, including hydroponics (Joshitha et al., 2021). The sensor network used in IoT can continuously monitor and control the health and growth of crops. All essential macro- and micronutrients required for crops are delivered to the plant through channels or other media (Trejo-Téllez et al., 2012). Agronomic growth variables can be both monitored and controlled by farmers through application interfaces directly connected to the cloud that stores real-time data (Palande et al., 2018).

Using IoT and automation techniques, a digital twin for hydroponics was developed that measures parameters such as pH, EC, water humidity and temperature in real-time and also predicts the growth and fresh weight of crops (Reyes et al., 2022). Boonnam et al. (2017) designed a hydroponic system using IoT and a wireless sensor network (WSN). Different important parameters, such as light, humidity and temperature, were controlled using this system. The data obtained from the sensors was continuously sent to the cloud for storage and further use. The parameters were controlled using a mobile application.

Recently, there have been reports about a smartphone application developed in Android Studio that allows users to adjust and monitor plant growth in hydroponic vertical farming systems. Using Internet of Things (IoT) technology, sensors are used to monitor environmental and dietary factors, including temperature, humidity, TDS, pH and water level. The Thing-Speak cloud platform was then used to send the data. The Tashi Home Pindfresh system and Arduino and Raspberry Pi were used as control centers (Kaur et al., 2022).

Despite these advantages, the monitoring and control of IoT parameters face challenges such as the lack of standards, high initial costs and security issues caused by network encryption (Gillani et al., 2022).

AI and ML for parameter optimization

Artificial intelligence (AI) and machine learning (ML), combined with big data and IoT, are driving the digitalization of agriculture. These technologies have the potential to improve real-time monitoring, increase production and achieve greater control over crop growth (Talaviya et al., 2020). ML algorithms and techniques are implemented in various aspects of agriculture, including crop management (yield prediction, species recognition, disease detection), and water and soil management (type, pH, temperature, moisture content) (Liakos et al., 2018).

A hydroponic system based on multimodal data analysis has demonstrated the ability to monitor and optimize six growth parameters (ambient temperature, airflow speed, relative humidity, CO_2 concentration, pH, EC and nutrient solution temperature) related to plant growth in a hydroponic plant factory (Lam et al., 2020).

A group of researchers has developed a control kit applicable to any hydroponic system of any size to control some of the growth parameters (pH, EC, nutrient solution temperature) at an optimal level. This kit was able to increase lettuce production by 21% compared to uncontrolled growth (Chuah et al., 2019).

A test bed based on an open IoT platform has been developed for monitoring hydroponic systems. It optimizes and monitors parameters, sends alerts if the parameters are not within optimal limits and estimates energy consumption. This testing platform provides essential information regarding the optimization and correlation of various growth parameters (Chowdhury et al., 2020).

Control of parameters in hydroponics 4.0/5.0

Hydroponics offers a solution to food insecurity, enhances sustainability and allows the integration of modern technologies (Shareef et al., 2024).

In 2021, the European Commission officially adopted Industry 5.0, which emphasizes sustainable, resilient and human-centric production systems and technology (Xu et al., 2021; Maddikunta et al., 2022). The application of Industry 5.0 principles in hydroponics, referred to as Hydroponics 5.0, can significantly improve agricultural production and its quality. For hydroponic systems, a cyber-physical cognitive system (CPCS) can be developed, capable of perceiving situations and taking corrective actions accordingly. This involves assigning repetitive tasks, such as monitoring parameters, controlling and optimizing subsequent actions to cobots (collaborative robots), while humans handle critical thinking. Digital twins can help detect diseases and predict yield/growth, leading to better control during the growth period. This approach paves the way for sustainable, resilient, and climate-smart hydroponic systems (Abbasi et al., 2022; Xu et al., 2021; Maddikunta et al., 2022).

CONCLUSIONS

The quality and quantity of crops produced, as well as the effectiveness of the growing environment and environmental preservation, are all greatly enhanced by the hydroponics techniques approach. The main benefit is that, in comparison to traditional agriculture, water usage can be reduced by up to 90% because the system is closed and the water is recirculated.

This growing method is perfect for cramped areas and urban settings since it saves space and makes effective use of light. Growers can transform their terraces and balconies into fruitful little gardens so they can unwind while caring for their own crops and enjoying the results of their labor.

When we talk about hidroponics we talk about a wide range of techniques that allow better control of climate and plant protection factors making it a promising agricultural alternative for the future.

Is a method that increases the quality and productivity of crops by avoiding the use of pesticides while having reduced problems with diseases and pest pests.

The most difficult issue with hydroponic agriculture is the constant need to maintain and regulate the artificial growing environment to allow for optimal plant growth. This type of crop is easily adaptable and enables the integration of contemporary agricultural technologies to automatically provide ideal growing conditions (with the help of sensors regulating pH, humidity, temperature, etc.) throughout the cycle.

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