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Optimizing Hydroponics Farming: A Comprehensive Review of AI and IoT Integration for Enhanced Efficiency and Sustainability

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Innovative techniques for sustainable agriculture, such as hydroponics and aeroponics, have come to light as viable answers to problems with food security. The present review delves at the ways in which Artificial Intelligence (AI) and the Internet of Things (IoT) might be combined to optimize farming methods, with an emphasis on improving sustainability and efficiency. This article examines artificial intelligence's involvement in smart farming and highlights how it helps with decision-making, crop monitoring, and predictive analytics. The usefulness of IoT technologies for automated system management and real-time data collection in controlled environment agriculture is also highlighted. The research goes into additional detail on the complementary ways that AI and

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IoT work together to increase crop yields and resource efficiency. Furthermore, scalability, affordability, and technical knowledge constraints and opportunities are examined. The study also assesses the benefits and drawbacks of hydroponic technology, weighing its advantages for the environment against possible drawbacks like setup fees. Ultimately, the future of controlled environment agriculture is shaped by developing technologies, AI-driven model developments, and Internet of Things innovations. These are the study areas and future trends that are identified. The goal of this thorough analysis is to shed light on the state of artificial intelligence (AI) and Internet of Things (IoT) applications for hydroponic and aeroponic farming.

Keywords: Hydroponics farming; Ai and Iot Integration; sustainability; farming methods.

1. INTRODUCTION

The pressure to meet the growing demand for food increases on traditional agricultural systems as the world's population continues to rise. As a result, modern agricultural method hydroponics have become popular. These soilless cultivation techniques have the potential to increase crop yields, make better use of available resources, and enable food production in places where conventional farming is not practical. By using less water and nutrients, these methods not only improve food security but also advance sustainable agriculture. The term "soilless culture" mostly describes hydroponic and aeroponic farming methods (Shrestha and Dunn). The roots of terrestrial plants can be cultivated in an inert medium, such as perlite, gravel, or mineral wool, or they can be grown only in the mineral nutrient solution. The process of growing plants without soil by submerging their roots in a nutrient solution is known as hydroponics (Sardare et al. 2019).

An enclosed air, water, and nutrient habitat that promotes quick plant development without soil or medium, with little water and direct sunlight, is known as an aeroponic system (Kumari and Ramesh 2019). Conventional hydroponics, aquaponics, and in-vitro (plant tissue culture) cultivation are not the same as aeroponic culture (Gopinath et al. 2017). The world would need to produce 50% more food to feed its projected 2050 population, which would need additional arable land that would not be available. By 2050, there will be less than 0.20 hectares of arable land per person, which is less than one-third of what there was in 1970, as demonstrated in Fig. 1 (Rathor et al. 2024).

Table 1. Comparison between hydroponics and traditional farming: (Comparison 2024)

Criteria	Hydroponics	Traditional farming
Efficiency and Yield	Higher efficiency and yield due to controlled environment.	Dependent on natural conditions, generally lower yield.
Space Requirements	Less space is required due to vertical farming.	It requires more land area.
Water and Resource Usage	Uses less water but may require more energy.	Uses less water but may require more energy.
Environmental impact	More sustainable, less impact on soil and water.	Can contribute to soil degradation and water pollution.
Climate-proof	Can contribute to soil degradation and water pollution.	Dependent on climate and weather conditions.
Crop variety and flexibility	Limited to certain types of crops.	Can grow a wider variety of crops.
Seasonal Dependency	Not dependent on seasons.	Season-dependent.
Contamination Risk	Lower risk due to controlled environment.	Higher risk due to open-air farming.
Food Waste	Less food waste due to proximity to consumers.	More food waste due to longer transit times.
Initial investment and management cost	Higher initial investment but potentially lower maintenance costs.	Lower initial investment but potentially higher maintenance costs.

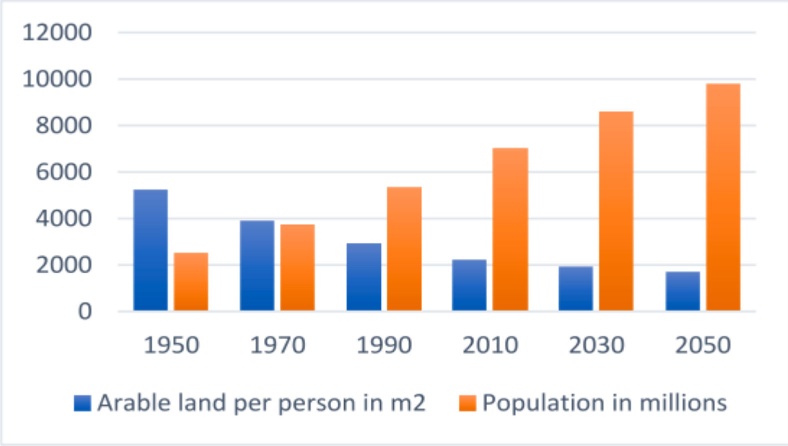

Fig. 1. Growing world population and declining agriculture land

2. ROLE OF AI IN SMART FARMING

According to the latest research, crops may be produced at exponentially higher rates if the right circumstances and essential nutrients are provided, which vary depending on the type of crop (KSH. 2020). The artificial intelligence (AI) model known as an artificial neural network (ANN) simulates the problem-solving abilities of biological nerve cells called neurons. An artificial neural network (ANN) with many layers that trains its models by modifying its weights through optimization techniques like gradient descent algorithms is called a convolutional neural network (CNN) (Musa et al. 2022). Unlike conventional techniques that rely on manually generated features, CNNs are a type of artificial neural network that excel at classification and image recognition by automatically extracting features straight from raw picture data (Kurian et al.). By preventing nutrient overload by turning off pumps in reaction to high TDS values, maintaining ideal pH and temperature ranges for steady plant growth, and modifying pump operations based on real-time TDS readings, the fuzzy logic control system efficiently maintained nutrient levels (Putra et al. 2024). Information from multiple sensors that measure environmental parameters like air temperature and humidity, pH levels, water temperature, electrical conductivity, and ambient temperature is gathered for data analysis. The pH sensor tracks changes in nutrient content and acidity; the temperature sensor evaluates moisture content; and the water temperature sensor measures nutrient content, and electrical conductivity measurements regulate the concentration of nutrient solutions (Mamatha and Kavitha 2023).

Several machine learning models, such as Support Vector Machine (SVM), K-Nearest Neighbor (KNN), and Multiple Linear Regression (MLR), have been extensively used as classifiers in the anomalous areas detection of crop leaves (Yang et al. 2023). 90.5% classification accuracy was achieved by using Fisher discriminant analysis to identify anthracnose crown rot in early stages of diseased strawberry leaves indoors (Lu et al. 2017). Enhanced moth-flame to identify early blight and powdery mildew on leaves, achieving 90.5% classification accuracy (KSH 2020). Developed prediction models using machine learning (MLR) for apple leaf samples in the early stages of Marssonina blotch and attained 92.0% classification accuracy (Shuaibu et al. 2017).

3. IOT APPLICATIONS IN CONTROLLED ENVIRONMENT AGRICULTURE

The term "Internet of Things" (IoT) refers to the network of wireless sensors and actuators that are buried in the earth to monitor and regulate various soil properties, including pH levels, moisture, nutrients, and electrical conductivity. One of the main challenges facing IoUT technology is protecting sensitive electronics inside wireless sensor nodes and minimizing wireless signal transmission loss (QAZI et al. 2022). Simple soil characteristics, such as pH, temperature, and humidity, are monitored and sent to a smartphone over Bluetooth. Farmers are then given access to the data to assist them in selecting crops and fertilizers (Misal et al. 2023).

The integration of Internet of Things (IoT) technologies into Controlled Environment

Agriculture (CEA) systems is one noteworthy advancement in modern agricultural practices. The Internet of Things (IoT) increases the productivity and efficiency of agricultural operations by utilizing a network of interconnected devices, including various sensors, actuators, and communication systems. By tracking vital environmental parameters, including temperature, humidity, CO2 levels, light intensity, and soil moisture, sensors give real-time data that enables precise regulation of growing conditions (Wong et al. 2021. Actuators, such as temperature control units and automated watering systems, modify these parameters based on sensor data to maintain the optimal conditions for plant growth (Martin and Smith 2022). Wi-Fi, Zigbee, and LoRa protocols are used by connectivity solutions to guarantee smooth communication between devices, and edge or cloud computing data processing enables real-time analysis and decision-making (Lee and Kim 2023, Zhang and Liu 2021). Among the many uses of IoT in CEA are climate control (Nguyen and Chou 2021); irrigation management (O'Brien et al. 2022) that optimizes water use based on soil moisture levels; and nutrient management (Jones and Martin 2022) that modifies nutrient delivery in hydroponic systems; pest and disease management (Rogers and Thompson 2023) that allows for early detection through sophisticated sensors and imaging; and energy management (Lee and Kumar 2021). These applications have many advantages, including greater productivity, enhanced crop yields, better resource management, and lower labor costs. But there are obstacles to overcome, like exorbitant expenses, worries about data security, problems with integration, and low technical dependability. It is anticipated that current research and future IoT technological improvements, such as those in artificial intelligence and machine learning, will expand the potential of IoT in CEA and encourage more productive and sustainable agricultural methods.

4. RELATION BETWEEN AI AND IOT IN HYDROPONICS

Through the creation of a more data-driven, effective, and sustainable approach to food production, the integration of artificial intelligence (AI) and the Internet of Things (IoT) in hydroponics is revolutionizing the agricultural sector. Sensors, cameras, actuators, and other Internet of Things (IoT) devices continuously gather data in real-time on important parameters including temperature, nutrition levels, light intensity, pH, and water quality. After that, AI algorithms analyze this data to forecast plant development outcomes, optimize environmental conditions, and identify possible problems like disease or nutrient deficiencies before they have an impact on production. In order to increase agricultural output, AI models, especially those based on machine learning and neural networks, can even make exact recommendations for modifying resource levels. Artificial Intelligence reduces human error and enhances decision-making by automating the study of massive datasets.

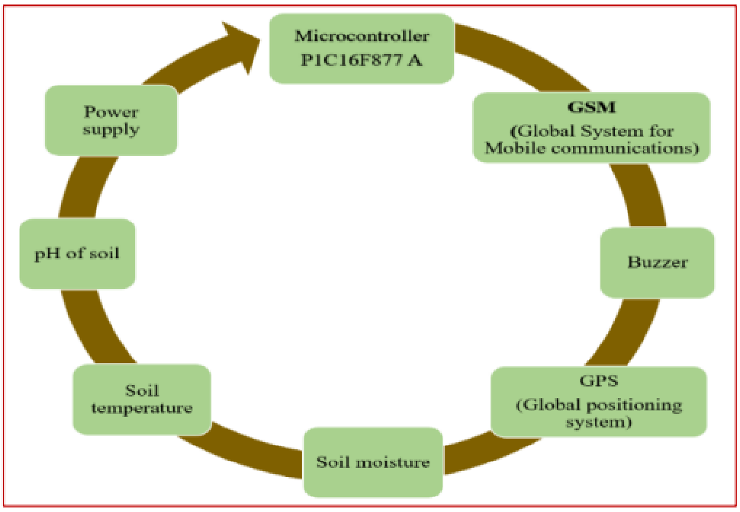

Fig. 2. Smart System Monitoring of Soil Using Internet of Things (Sowmiya and Sivaranjani 2017)

Table 2. Yield Comparisons between hydroponic and open field cultivation (Khan et al. 2018)

Types of Crops	Names of Crops	Hydroponics Yield (Kg per ha)	Open Agriculture Yield (Kg per ha)
Cereals	Rice	13,456.6	841.03-1,009.25
	Maize	8971.	1,682.07
	Wheat	5606.9	672.83
	Oat	964.14	953.18
	Soyabean	1682.07	672.82
Vegetables	Tomato	403,335.81	11,203.75-22,407.47
	Beet	22,427.6	10,092.42
	Potato	156,852.29	17,925.98
	Cabbage	20,184.84	14,577.94
	Cucumber	31,398.64	7,849.66

Table 3. Summary of recent technological advancements in hydroponics, highlighting their main advantages and disadvantages (Peñailillo et al. 2023)

Advanced Hydroponic Technology	Main Advantages	Main Disadvantages
AI-Based Monitoring Systems	High precision in nutrient and pH detection, yield optimization	High cost, technical skills required for operation
Precision agriculture techniques	Efficient resource use, improved crop quality	High initial investment, complexity in implementation
Advanced Moisture and Nutrient Sensors	Real-time monitoring, improved irrigation efficiency	Installation and maintenance cost, potential technical failures
Automated Climate Control Systems	Precise environmental control, improved crop quality, and yield	High energy consumption, operational costs
Mobile apps for crop management	Remote access for monitoring and control, ease of use	Connectivity dependency, feature limitations depending on the app
Full-Spectrum LED Lighting	Energy efficiency, improved plant growth	High initial cost, potential for plant stress if not managed correctly

IoT networks also make it possible to remotely monitor and manage hydroponic systems, giving farmers the ability to react to changes and oversee operations from almost any location. This clever farming method increases yields and more reliably maintains plant health while using resources like water and electricity down to a maximum of thirty percent less (Shamshiri et al. 2018). Furthermore, AI systems have the capacity to recognize trends and abnormalities over time, which enables proactive modifications and predictive equipment maintenance that maximize system efficiency (Kalantari et al. 2021). Hydroponic farming becomes more ecologically friendly and scalable when AI and IoT are combined, which makes it a possible answer to concerns related to global food security and urban agriculture (Maharana and Koul 2011).

5. INTEGRATION OF AI AND IOT

The convergence of artificial intelligence (AI) and the Internet of Things (IoT) is a game-changer in a number of industries, including smart cities, healthcare, and agriculture. AI improves IoT systems by offering predictive modeling, autonomous decision-making, and sophisticated data analytics. More precise insights and forecasts are made possible by the application of AI algorithms to the massive volumes of data that IoT devices collect. AI-driven Internet of Things (IoT) systems, for instance, can evaluate sensor data to forecast crop illnesses, improve irrigation schedules, and effectively manage resources in the agricultural sector (Zhao et al. 2021). According to (Khan et al. 2022), this connection makes it easier to monitor and regulate operations in real-time and enables dynamic modifications based on predictive analytics, which enhances operational efficiency and results. Analogously, AI-driven Internet of Things (IoT) systems in smart cities collect information from several sensors in order to evaluate and decide on ways to enhance public safety, maximize energy efficiency, and manage traffic patterns (Jin et al. 2023). As a result, the integration of AI with IoT enhances the intelligence and functionality of linked systems, promoting productivity and innovation across several industries.

There are many case studies and illustrations of how cutting-edge technology like hydroponics and vertical farming have been successfully used to grow crops in controlled surroundings. One such instance involves the Newark, New Jersey-based startup AeroFarms, which grows leafy greens and herbs indoors through vertical farming. Their innovative aeroponic method delivers nutrients to plants through a mist, accelerating growth and increasing yields. According to AeroFarms, their vertical farms can produce up to 390 times more crops per square foot of land and require 95% less water than conventional farms (AeroFarms). Another well-known enterprise using vertical farming to grow a range of crops, such as leafy greens, berries, and vine vegetables, is Plenty, situated in San Francisco. To maximize plant development, their indoor farms make use of climate control systems, automated nutrient supply, and LED lighting. In 2020, Plenty and renowned berry producer Driscoll's collaborated to create new strawberry cultivars tailored for vertical farming (Plenty).

6. CHALLENGES AND OPPORTUNITIES

There are numerous challenges involved in the construction of a hydroponics system. Hydroponics requires a high initial investment. (Tyson et al. 2024) state that a hydroponic garden's surface area should support a minimum of 40 large plants (such as tomatoes, bell peppers, and banana peppers) and a minimum of 72 tiny plants (such as lettuce, spinach, and strawberries). When installing an Arduino-based temperature control system, a number of considerations should be made, including the system's availability, efficiency, and shipping costs. The system's initial cost should also be determined by these considerations (Taig 2012). A literature review indicates that the price range for an Arduino-based climate control system for a commercial hydroponic greenhouse is between $500 to $2000 USD (Grewal et al. 2021; Takakura 2014).

An advanced degree of supervision is required for hydroponic greenhouses. High managerial abilities are necessary for the commercial production of any crop in a hydroponic greenhouse system, according to (Shaw eta l. 2001). The degree of management is determined by the system's complexity (Higashide eta l. 2013). Particularly in a tropical region with drastic seasonal variations, an automated system for routinely monitoring and controlling the temperature inside a hydroponic greenhouse should be able to provide adequate heating in the winter and cooling or shade in the summer (Kuennen et al. 2008).

7. ADVANTAGES AND DISADVANTAGES OF HYDROPONICS TECHNOLOGY

7.1 Future Trends and Research Directions

Hydroponics has advanced significantly in terms of both technology and public acceptance, but a number of factors will determine how successful this farming technique is in the future. Future developments in hydroponics are bringing the industry closer to a time when soilless farming systems may include essential elements of automation, artificial intelligence, and even nanotechnology (Singh et al. 2023). We simply need to look at a few of the pioneers in this field to get an idea of where hydroponics is headed (Singh and Singh 2012). In hydroponic farming, rice is harvested four times a year as opposed to just once in open-field agriculture (Van et al. 2002). Millions of people could be fed by hydroponic greenhouse systems in third-world countries in the future due to the scarcity or threat of water and crops in those areas. Although the initial cost of installation is high, over time all costs will decrease, making this technology more practical and affordable (Raviv et al. 1998; De Kreij et al. 1999). Given its global adaptability, it is reasonable to expect that this technology will have a bright future.

7.2 AI Startups in Smart Agriculture

a) Prospera, 2014

This AI-powered gadget can be utilized in farms or greenhouses. Numerous climatic sensors, technology, and in-field cameras power it. The input from these sensors provides real-time analysis of the field operations, which allows farmers to manage pests, diseases, irrigation, nutrient deficits, and other agro-technical activities.

b) Blue River Technology, 2011

This firm is focused on lowering the usage of dangerous chemicals, saving farmers' expenses, and increasing agricultural output while having the least negative effects on the environment. Their goal is to develop robotics and machine learning to enable the production of intelligent machinery on a global basis (Hassanien et al. 2017)

c) Agro2o

A firm in Delhi that has created a prototype for a "smart hydroponic garden" incorporating AI and IoT growing algorithms. The creator of Agro2o enlisted AI's assistance to address conventional hydroponics problems, such as the requirement to maintain constant pH levels and electrical conductivity (AI).

d) Agritech

Worked on obstacles such as inclement weather. They used smart precision technology, which measures humidity and determines water measurement by fusing artificial intelligence (AI) with machine learning and 5G (AI).

8. CONCLUSION

Hydroponics farming have revolutionary prospects due to the integration of AI and IoT technology. This allows these farming systems to become more sustainable, efficient, and flexible in response to the increasing demands for food security. When paired with IoT's real-time data monitoring and AI's predictive analytics, resource optimization, and automated decision-making capabilities, they form a potent combination for controlled environment agriculture. Even if there are still difficulties, including high implementation costs, data privacy issues, and technological complexity, the advantages—such as increased crop yields, less environmental impact, and less resource consumption—far outweigh these drawbacks. AI and IoT-enhanced hydroponics present a viable route forward for sustainable agriculture. Going forward, overcoming current obstacles and achieving the full potential of these sophisticated farming systems will require ongoing research and innovation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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