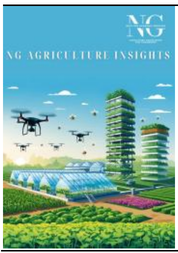

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Smart Farming with IoT: A Paradigm Shift in Hydroponic Cultivation of Leafy Greens

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A B S T R A C T

The use of Internet of Things (IoT) technologies in hydroponics is a great contribution to sustainable agricultural development. This review examines the contribution of the rarely discussed IoT-driven systems in the enhancement of the production of green leafy vegetables by offering precise environmental control, real-time monitoring, and automation. Components of IoT, like sensors, actuators, and cloud-based analytics, will be used to optimize the use of water, nutrients delivery, lighting, and climate, resulting in a better crop yield, lower utilisation of resources, and the capacity to produce crops throughout the year. The most notable advantages are a higher water performance, reduced chemicals and the possibility of urban and vertical agriculture. Nevertheless, the main issues, including high startup costs, technical sophistication, and the need to maintain stable connectivity, stay in place. What is also outlined in the article are the advancements that are likely to be innovated in the future, AI-based automation, blockchain as a method to trace food, and renewable energy integration. In general, the IoT-enabled hydroponic system is a scalable, productive, and climate-adaptive system of organising food systems, in particular, in shortening cities, food security, and environmental sustainability amid global pressures in agriculture.

Keywords: Automation, Hydroponics, Internet of Things, Smart Farming, Sustainable Agriculture

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1. INTRODUCTION

The uncontrolled rate of world population, the inflation of cities, and climate swings have severely challenged traditional agriculture as it strives to provide people with safe, nourishing, and environmentally sound food in ever-growing quantities. Challenges like the decrease in soil fertility, erratic weather patterns, shortage of water and the excessive application of agrochemicals are becoming problems in the conventional soil-based farming systems. Not only do such factors make the productivity unreliable, but they are also a serious health and environmental threat. To address these problems, smart farming, which uses the power of present technologies such as the Internet of Things (IoT), artificial intelligence (AI), and automation in agricultural processes, has become a radical solution (Prusty et al., 2025).

Among other things, IoT-based hydroponics has become one of the most interesting smart farming uses. Hydroponics is the farming of plants in nutrient-rich water solutions, and gives the possibility of precise control of plant nutrition and growth parameters. By means of augmenting with technologies of IoT, this approach to cultivation is once more potent and effective. Monitoring using an interconnected network of actuators and sensors across IoT enables real-time monitoring of critical

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parameters like pH, temperature, humidity, light intensity, levels of nutrients and so on (Suman et al., 2024). When insight is gained on the basis of data, automated responses can be made that enable the best conditions to be achieved in continuing plant health and productivity (Austria et al., 2023). Emerging analyses of protected-cultivation setups further underline that sensor-driven, automation-rich environments will dominate sustainable horticulture in the coming decade (Aditya et al., 2023).

The most trainable of the green leafy vegetables are lettuce, kale, spinach and arugula because of the fact that they have short growth cycles, light frames and high demand in the market. The integration of the accuracy of the IoT system with the resource optimisation of the hydroponic system helps farmers harvest leafy greens in controlled environments that can withstand external disturbances and are built to ensure sustainability. The synergy saves water and land, fosters cultures year-round and minimises the use of chemicals in addition to the urban and peri-urban infrastructures of farming (Nikolov et al., 2023).

2. IOT SYSTEM ARCHITECTURE IN HYDROPONIC FARMING

The effectiveness of smart hydroponic agriculture is dependent on a feature-packed architecture of the Internet of Things (IoT), combining sensing technologies, automation tools, and cloud computing with the user interface. The interactions that take place on this system enable real-time monitoring and also autonomous decision making, resulting in high accuracy in controlling the environment in which plants grow.

2.1. *Environmental Monitoring with Sensors*

A hydroponic system based on the IoT has a heavy amount of environmental sensors at its core. The sensors gather real-time information on different parameters that are critical to plant health and productivity. Sensors of temperature and humidity control the microclimate to achieve maximum photosynthesis and transpiration. pH and electrical conductivity (EC) sensors show the chemical composition of the nutrient solution, so that plants would get the right ratio of nutrients. The intensity of light is determined, and the period of light is vital to leafy greens with special photoperiods, using light sensors. Also, the concentration of carbon dioxide (CO_2) in the air is measured with the help of carbon dioxide (CO_2) sensors, providing a possibility to regulate the photosynthetic atmosphere in a fine-tuned mode (Yusuf et al., 2022).

2.2. *Automation and Actuation Systems*

The sensor information is fed to an automation control module, typically a microcontroller or IoT hub, where the input feed is processed and used to initiate particular actions. The important aspects that are controlled by this automated system are dosing of nutrients, circulation of water, control of lighting and creating a climate. Nutrient solutions are distributed by water pumps with time periods that are linked to the stage of maturity of the plants. LED grow lights are also programmed to keep them at the optimal light strength day and night. Such pieces of equipment as fans, heaters, and humidifiers are turned on to introduce climate control so that the humidity and temperature are maintained within reasonable limits.

2.3. *Cloud Analytics and Artificial Intelligence*

IoT solutions usually include the use of cloud-based analytics with the help of artificial intelligence (AI) in order to improve decision-making. The gathered data is uploaded to cloud removing systems where it is processed, analysed and visualised. AI algorithms are about to detect the tendency and make predictions about the possible failure of the system, and offer changes in accordance with the previous patterns. Such data-driven practice will allow farmers to take proactive and intelligent decisions; this would enhance the harvest and the efficiency of the system (Rahman et al., 2024).

2.4. *Remote Access and User Interface*

One distinguishing characteristic of smart hydroponics is the fact that one can monitor and control farm activities remotely. The user can receive results in real-time through mobile applications or web-based dashboards, be alerted of changes, and even interface with automated settings to override them when necessary. These interfaces are highly meant to be user-friendly, thus eliminating the learning curve regarding technology among the farmers, and the farmers can embrace smart farming practices better.

3. BENEFITS OF IOT-DRIVEN HYDROPONIC CULTIVATION

A combination of IoT technologies with hydroponic systems will provide a package of revolutionary advantages, increasing productivity, sustainability, and profitability. Such advantages included environmental efficiency, crop performance, spatial optimisation, and economic resilience, which makes IoT-based hydroponics a very strong model in modern agriculture.

3.1. Water Efficiency and Conservation

Among the first benefits of hydroponic agriculture, in particular, IoT-driven, is its outstanding degree of water conservation. Conventional soil agriculture results in the loss of water by means of evaporation, rain, and drainage. On the contrary, hydroponics is a method of water recirculation in a closed cycle that decreases water consumption (up to 90%). Water distribution is made even more precise when IoT sensors are used to inspect the moisture levels and nutrient concentrations (Regmi et al., 2024). This will make crops have access to water that is just as much as is needed, and thus there will be no wastage, and one of the most important resources in agriculture will be preserved.

3.2. Enhanced Crop Yield and Growth Rate

IoT systems enable incessant enhancement of conditions of growth, such as the amount of light, the availability of nutrients, or an optimal temperature. The result is a desirable microenvironment of plants with increased rates of vegetative growth and yields due to such precise control. Leafy greens are especially thriving under such ideal conditions, so much as to grow up to 30-50 per cent faster in a hydroponic system than their traditional counterpart, in the soil. It has produced a more predictable and productive cultivation cycle that has the highest returns on investment (Choudhary et al., 2024).

3.3. Year-Round Cultivation and Climate Independence

IoT-driven hydroponic farms are much more self-sufficient in relation to the outside weather changes, since the controlled systems are run under artificial conditions, either inside a highly restricted setting or a greenhouse. This will make production possible all year round despite changes of seasons, droughts and floods. The controlled environment lessens the perils posed by pests and is a consistent weather incident, and crop diseases, which gives rise to a more steady and resilient farming paradigm.

3.4. Space Optimisation and Urban Farming

There has been a decline in the number of lands going to cultivation due to urbanisation, which is one of the major concerns; however, vertical and rooftop farming using IoT-based hydroponics can solve this problem. They are modular systems and can be used in cities, in buildings/basements or even in shipping containers. The capacity to produce high-quality produce in locales that were not natural farming grounds helps in food security and helps to cut the gap between production and consumption.

3.5. Reduced Chemical Usage and Safer Produce

This controlled environment in the hydroponic agriculture considerably reduces chemical pesticides and herbicides. Subsequent crops are exposed to fewer and no harmful chemicals since fewer and no pests and weeds are exerted on them. Monitoring systems based on IoT have the potential to identify the beginning of nutrient shortage or disease and fix it in time without extensive implementations in widespread use of chemicals. It leads to cleaner and healthier produce that responds to the rising needs of consumers for sustainable and organic foods.

3.6. Cost Reduction and Operational Efficiency

In spite of the high initial investment in the IoT infrastructure, operational costs are not high most of the time in the long run. Routine processes of irrigation, lighting and nutrients are automated, so that less labour is needed and less error occurs. In addition, predictive analytics and analytics in general allow avoiding crop loss, assisting in forecasting dangers early, and minimising losses, cutting expenses, and raising profitability. IoT farming is data-driven and, thus, promotes efficiency and scalability since it is possible to optimise it indefinitely (Choudhary et al., 2024).

4. CHALLENGES AND LIMITATIONS

Verging on the high cost of initial investment is one of the most important hurdles to implementing the IoT-based hydroponic systems. The price of sensors, control units, automation equipment, cloud computing and energy-efficient lighting may be too high, especially for small-scale farmers and start-ups. Although these expenses are usually covered through the enduring savings in labour, water and inputs, the initial capital outlay can be a big obstacle (Das et al., 2025). Widespread adoption could be effected by subsidies, cooperative ownership or incentives.

The next big setback is the technical expertise that is needed to run such systems. Activities such as sensor calibration, data interpretation, and maintenance of the system require skills that many traditional farmers lack. In the absence of training or less user-friendly systems, there is a possibility of misusing the system or its inefficiency. The only way to eliminate this barrier lies in education and capacity-building (Saha et al., 2024).

Their effectiveness is also constrained by the need for stable internet and electricity, particularly in remote locations. Reliability could be enhanced by adding solar power, battery backup and edge computing. Finally, the deterioration of sensors and the absence of hardware-software standardisation is a long-term operation and growth problem. Maintenance and modular system building are essential for frequent performance and more integration.

5. CONCLUSION

Hydroponic farming with IoT provides a revolutionary way of modern agriculture that meets the challenge of water shortage, Climatic diversity, and food security in urban areas. These systems maximise the growth conditions of the plant in real-time via automation and AI-based analytics tools and thereby enhancing efficiency and crop yields notably in the case of high-growth leafy greens. The technology allows them to grow all year long, it minimises the application of pesticides, and facilitates small-spaced urban farming. Although the challenge of the upfront cost and technical skills required to achieve it remains an important obstacle, the developments in the modular system design, interface, and the integration with renewable energy sources make these systems increasingly affordable. Moreover, the blockchain usage has the ability to make food supply chains more transparent and trustworthy. Due to the increasing rate of urbanisation and pressure on the environment, hydroponic farming fueled by IoT is one of the viable, expandable, and green models of food production. It has huge potential in designing strong and robust agricultural systems capable of satisfying the eating requirements of posterity generations with a little environmental footprint.

REFERENCES

Aditya, P., Rao, V., Mohapatro, S., Chandra, V., Nanda, C., & Suman, S. (2023). Future trends in protected cultivation: A review. *The Pharma Innovation Journal, 12*(8S), 2025–2029.

Austria, A. H., Fabros, J. S., Sumilang, K. R. G., Bernardino, J., & Doctor, A. C. (2023). *Development of IoT Smart Greenhouse System for Hydroponic Gardens*. *arXiv*. https://doi.org/10.48550/arXiv.2305.01189

Choudhary, U., Senapati, P. K., Kumar, R., Kumar, A., & Sahoo, N. (2024). Hydroponics: Per drop more crop for food safety—A review of technological progress and challenges. *Journal of Agriculture Biotechnology & Applied Sciences, 2*(3), 108–118. https://doi.org/10.5281/zenodo.13954796

Das, N., Modak, S., Prusty, A. K., Saha, P., & Suman, S. (2025). Understanding and overcoming key challenges of agripreneurs in southern Odisha: A case study. *Indian Journal of Extension Education, 61*(2), 118–122. https://doi.org/10.48165/IJEE.2025.612RN05

Nikolov, N. V., Atanasov, A. Z., Evstatiev, B. I., Vladut, V. N., & Biris, S.-S. (2023). *Design of a small-scale hydroponic system for indoor farming of leafy vegetables*. *Agriculture, 13*(6), 1191. https://doi.org/10.3390/agriculture13061191

Prusty, A. K., Saha, P., Das, N., & Suman, S. (2025). Implementation and adoption of smart technologies in agri-allied sectors. *Plant Science Today, 11*(sp2). https://doi.org/10.14719/pst.3467

Rahman, T., Islam, M. S., & Hossain, F. (2024). An AIoT-Based Hydroponic System for Crop Recommendation and Nutrient Parameter Monitoring. *Engineering in Agriculture and Applied Technology Studies*, 12(3), 148–162. https://doi.org/10.1016/j.engapptech.2024.05.008

Regmi, A., Rueda-Kunz, D., Liu, H., Trevino, J., Kathi, S., & Simpson, C. (2024). *Comparing resource use efficiencies in hydroponic and aeroponic production systems*. *Technology in Horticulture*, 4, e005. https://doi.org/10.48130/tihort-0024-0002

Saha, P., Prusty, A. K., Nanda, C., Ray, S., & Sahoo, B. (2024). Professional insights provided by women extension personnel in Odisha. *Indian Journal of Extension Education, 60*(3), 101–105. https://doi.org/10.48165/IJEE.2024.603RN03

Suman, S., Deb, A., Prusty, A. K., Sameer, S., Divya, B. S., & Saha, S. (2024). *Utilizing blockchain, IoT and machine learning for transparent agri-extension and resource distribution: A review*. In 2024 2nd International Conference on Signal Processing, Communication, Power and Embedded Systems (SCOPES) (pp. 1–6). IEEE. https://doi.org/10.1109/SCOPES64467.2024.10991113

Yusuf, A. F., Mahendra, R., & Kusumaningrum, I. (2022). Design and Development of an Internet of Things (IoT) Based Real-Time Monitoring and Control System for Smart Indoor Hydroponic Vertical Farming. *arXiv*. https://doi.org/10.48550/arXiv.2203.05342