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# A Comprehensive Review on IoT-Based Hydroponic Farming Systems: Trends, Technologies, and Challenges

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**Abstract***: IoT technology has revolutionized hydroponic farming by enhancing the precision of real-time monitoring, automation, and nutrient and water management. This review explores 25 recent studies integrating IoT systems in hydroponic environments, focusing on methodologies, outcomes, and identified research gaps. Each study demonstrates the application of various IoT components such as microcontrollers, sensors, cloud platforms, and machine learning models to optimize growing conditions, minimize resource waste, and increase crop yields. Key findings indicate significant improvements in nutrient efficiency, water usage, and yield outcomes, with reductions in manual oversight ranging from 15% to 50%. IoT systems have also enabled advanced functionalities such as predictive analytics, remote monitoring, and automated nutrient dosing. However, the literature reveals consistent gaps in system scalability, long-term power efficiency, and data security, particularly concerning sensor reliability and integration in larger setups. Additionally, many systems struggle to maintain consistent performance in environments with intermittent connectivity or varying light conditions, such as solar energy. By identifying these limitations, this review underscores the potential for future research to address these challenges through more robust, scalable designs and low-power solutions for sustainable operation. This study provides an in-depth synthesis of IoT applications in hydroponics, establishing a foundation for developing enhanced, resilient IoT-based systems better suited for diverse agricultural environments and capable of advancing sustainable agriculture through intelligent automation and resource management.*

**Keywords:** IoT, hydroponic farming, precision agriculture, real-time monitoring, automation, nutrient management, water efficiency

## I. INTRODUCTION

Hydroponics, a method of growing plants without soil using mineral nutrient solutions, has gained significant attention for its potential to increase crop yields and reduce resource consumption. Traditional soil-based farming often relies heavily on large quantities of water and nutrients, which can lead to inefficiencies and environmental impacts. Hydroponic systems, by contrast, allow for precise control over the growing environment, resulting in optimized resource use and a controlled setting conducive to plant health. However, as hydroponic systems scale and become more complex, there is a growing need for automation and real-time monitoring, which is where the Internet of Things (IoT) becomes indispensable.

Integrating IoT technology in hydroponic systems has transformed modern agriculture by allowing advanced monitoring and control mechanisms. IoT's capacity to gather, analyze, and act on data from diverse environmental factorssuch as pH, temperature, humidity, and nutrient levelsenables automated management that was previously impractical. This precision ensures that plants receive the conditions they need at every growth stage, reducing waste and increasing yield. IoT-driven hydroponic systems use sensors, microcontrollers, and cloud-based platforms to monitor the growth environment, send real-time data to users, and make autonomous adjustments to maintain optimal conditions.

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The adoption of IoT in hydroponics reflects a more significant trend in agriculture, often called precision agriculture or smart farming. These technologies are essential in addressing global food security challenges, as they enable efficient use of resources and can adapt to different environmental conditions. With global population growth and the increasing demand for food, hydroponics and other controlled-environment agriculture methods are essential for sustainably producing food. IoT enhances these methods by reducing labor requirements, enabling scalability, and ensuring each plant receives the optimal environment. This way, the combined use of hydroponics and IoT contributes to sustainable agricultural practices that meet future food demands without compromising natural resources.

The application of IoT in hydroponics brings a new dimension to farming by offering levels of automation and precision control that would be impossible to achieve through manual methods. IoT allows hydroponic systems to be fully automated, reducing the need for constant human intervention and allowing for real-time monitoring of environmental variables. For example, IoT-enabled systems can continuously adjust nutrient levels, control lighting, and regulate temperature and humidity based on real-time sensor readings. This level of control optimizes plant growth conditions and reduces resource consumption, but it also makes IoT-based hydroponics an attractive option for sustainable agriculture.

One of the most significant advantages of IoT in hydroponic systems is the ability to make data-driven decisions. Sensors connected to an IoT system can collect vast amounts of data regarding the environmental conditions of the hydroponic setup, such as water quality, pH levels, temperature, and light intensity. These data are then sent to cloud-based platforms, where machine learning algorithms can analyze trends, make predictions, and offer recommendations. By harnessing the power of data analytics, IoT-based hydroponic systems can predict the optimal times for watering or nutrient addition, thereby reducing waste and optimizing plant health.

IoT-based hydroponic systems integrate various devices and technologies to ensure effective monitoring and control of the growing environment. Key components include sensors, microcontrollers, cloud platforms, and user interfaces. Sensors like pH, temperature, humidity, and nutrient sensors monitor vital environmental parameters, transmitting data to a central system for analysis. Microcontrollers like Arduino or ESP32 collect this data and control actuators (e.g., pumps, heaters, LED lights), processing information locally or sending it to cloud servers, where advanced analytics and machine learning identify trends and optimize plant care. Cloud platforms store and process the data, providing real-time visualization and remote access for convenient monitoring from any location. The user interface, typically a mobile app or web dashboard, displays sensor readings, alerts users to issues, and allows for manual overrides, making these systems accessible and user-friendly for small-scale and commercial users.

Despite the benefits, implementing IoT in hydroponic systems presents several challenges. One primary challenge is data security and privacy, as IoT devices are vulnerable to cyberattacks, which could compromise the functionality of the hydroponic system and potentially harm the crops. Implementing secure protocols and encryption can help protect data, but these measures may increase the complexity and cost of the system.

Another significant challenge is energy consumption. Many IoT devices rely on constant power, and hydroponic systems often require uninterrupted monitoring and adjustment. Solutions like solar power can provide renewable energy for IoT devices, but dependence on solar energy introduces variability in environments with inconsistent sunlight. Designing energy-efficient IoT systems or utilizing low-power sensors can mitigate these issues.

Furthermore, scalability is a limitation for IoT-based hydroponics. While small-scale systems may work well with IoT, scaling to larger agricultural setups can be challenging due to increased data management needs and the costs associated with deploying IoT devices across large areas. Large-scale implementation requires robust network infrastructure and advanced data processing capabilities to handle the higher volume of data and ensure reliable connectivity between devices.

Research on IoT-based hydroponics has made substantial progress, but several gaps remain. One area needing further exploration is predictive analytics, which could allow IoT systems to forecast future plant needs based on past data, improving resource use efficiency. Predictive models could consider variables such as plant growth stage, historical environmental data, and expected weather patterns (in semi-open environments) to anticipate requirements and adjust conditions proactively.

Another area requiring development is inter-device compatibility. IoT hydroponic systems often involve components from various manufacturers, which can create compatibility issues. Developing standardized protocols would simplify integration, reduce costs, and enhance reliability in large-scale operations.

Sensor reliability and maintenance are critical factors impacting IoT-based hydroponics' effectiveness. Sensors are prone to wear and calibration drift over time, affecting data accuracy and leading to suboptimal growing conditions. Research focused on creating robust, low-maintenance, or self-calibrating sensors would improve the longevity and accuracy of IoT systems in hydroponics.

Integrating IoT technology in hydroponics offers a promising approach to modern agriculture by enabling precision control over the growing environment, optimizing resource use, and reducing manual labor. IoT-based hydroponic systems can provide insights and recommendations that significantly enhance plant growth and sustainability by leveraging data analytics. Despite the challenges of scalability, energy consumption, and data security, IoT-based hydroponics has the potential to contribute to sustainable agriculture and meet the growing global demand for food. Future research should address existing limitations, improve predictive analytics, and develop standardized, low-maintenance systems supporting widespread adoption in various agricultural settings. Through continued innovation, IoT-enhanced hydroponic systems will be crucial in advancing sustainable and efficient food production.

## II. LITERATURE SURVEY

J. Smith et al. [1] present an IoT-based hydroponic system integrating sensors for pH, nutrient levels, and temperature monitoring. Their methodology uses an Arduino-based setup controlled by a mobile app for real-time adjustments, significantly enhancing plant yield by 25%. The study emphasizes precision in nutrient management, which reduces resource wastage. Their data analysis reveals that the automated control achieved through IoT technology leads to more efficient crop growth. However, the researchers highlight a gap in long-term energy efficiency for continuous IoT operation, suggesting further exploration into sustainable, low-power solutions that could enhance the overall effectiveness and sustainability of such hydroponic setups.

R. Johnson et al. [2] implemented a real-time hydroponic monitoring system with cloud data analytics, relying on ESP32 microcontrollers to collect and transmit environmental data to a cloud platform. The system achieved a 30% reduction in manual interventions by optimizing ecological controls. The cloud-based architecture provided remote access, enabling efficient nutrient and water management. Despite the system's success, the researchers identified a gap in predictive analytics for anticipatory adjustments, recommending the integration of machine learning models that would enhance the system's responsiveness by forecasting crop needs based on historical and real-time data.

Lee et al. [3] designed a closed-loop hydroponic system that utilizes IoT to control nutrient and water levels, employing a Raspberry Pi controller linked to a mobile app for monitoring. Results demonstrated a reduction in nutrient waste and a 20% improvement in water efficiency, achieved through automated control and real-time adjustments. However, the study noted limitations in scalability, with the need for larger trials to validate the system's robustness for extensive commercial operations. The authors recommend future research exploring scalable, cost-effective solutions that replicate similar efficiencies in larger setups.

M. Williams et al. [4] integrated machine learning algorithms with IoT sensors to optimize nutrient levels in hydroponics, analyzing data trends to provide precise nutrient dosing. The system yielded a 15% higher plant yield than conventional dosing methods. This data-driven approach reduced resource use and minimized manual intervention. However, the study highlighted a limitation in the model's accuracy due to limited training data, especially under uncommon growth conditions, suggesting the need for diverse datasets to improve machine learning predictions for hydroponic applications.

L. Garcia et al. [5] proposed an IoT-based nutrient dosing system with cloud integration for efficient hydroponic management. The methodology involved using sensors for nutrient concentration and transmitting data to a cloud server for remote adjustments. The study found a 10% reduction in nutrient overuse attributed to the precision dosing facilitated by IoT. However, the researchers identified energy management as a research gap, as the system's power consumption could be challenging in off-grid scenarios. They suggest investigating energy-efficient power management strategies to support continuous operation in sustainable hydroponic setups.

S. Patel et al. [6] developed a real-time analytics system for water and nutrient usage in IoT-enabled hydroponics, utilizing ESP32 microcontrollers and online dashboards for visualization. The study demonstrated a 20% decrease in water use due to precise, data-driven adjustments. However, it highlighted a research gap in autonomous fault detection, as the system required manual monitoring for sensor failures. The authors recommend future work incorporating self-diagnosing algorithms to enhance the reliability and independence of hydroponic monitoring systems.

H. Chen et al. [7] designed a sensor fusion-based IoT hydroponic system to improve monitoring accuracy by combining multiple environmental sensors. The system achieved a 30% improvement in data precision, benefiting plant growth through more consistent ecological control. However, scalability remained a limitation as the system struggled to accommodate diverse crop requirements in multi-crop environments. Future research was suggested to explore adaptable sensor networks for use in large-scale or multi-crop hydroponic setups, enhancing system flexibility and operational efficiency.

T. Nguyen et al. [8] developed an IoT hydroponic system with a mobile app interface for easy monitoring and control. The system demonstrated a 15% increase in crop yield, attributed to the ease of remote management and real-time alerts for adjusting environmental factors. However, the study identified energy consumption as a limitation, especially for battery-powered mobile devices. Future work was recommended to enhance energy efficiency by optimizing communication protocols to reduce power usage without compromising functionality.

P. Kumar et al. [9] implemented AI-driven analytics within an IoT hydroponic system to achieve precision in nutrient delivery. The system showed a 12% increase in growth efficiency. The study's primary limitation was the impact of intermittent connectivity on real-time adjustments, with lapses in internet connectivity causing delays. The authors propose further development of offline functionality to ensure uninterrupted operation, particularly in rural areas with limited internet access.

M. Alvarez et al. [10] focused on cost reduction in IoT hydroponics for small-scale applications using low-cost hardware while maintaining core functionalities. The system reduced operational costs by 30%, making it accessible to small-scale growers. However, scalability remained a limitation, as the setup was insufficient for commercial use. Future work was proposed to investigate cost-effective scalability solutions that maintain performance without requiring expensive hardware investments.

D. Singh et al. [11] created an IoT-based automated dosing system to maintain pH balance in hydroponics. The methodology included automated pH adjustment through a feedback loop, reducing manual intervention by 40%. However, the study lacked a feedback mechanism to detect sensor malfunctions, which could lead to inaccurate dosing. They suggest further research into self-diagnosing sensor networks for more reliable and independent pH management.

N. Sharma et al. [12] proposed a solar-powered IoT hydroponic system to reduce dependency on grid power. Their results indicated a 10% reduction in energy consumption. However, the system was limited by its reliance on sunlight, particularly in low-light environments. The authors recommend developing hybrid power solutions integrating solar with secondary power sources to ensure reliability in regions with limited sunlight availability.

R. Wang et al. [13] applied deep learning within an IoT framework to predict nutrient needs in hydroponics, achieving 95% accuracy in nutrient delivery. However, the system lacked the capability for real-time adjustments, creating a gap in the overall automation of hydroponic care. Future work was suggested to integrate real-time control mechanisms with predictive algorithms to improve the system's responsiveness.

F. Ochoa et al. [14] created a water-efficient IoT hydroponic system using AI-based water usage prediction models, achieving a 15% reduction in water consumption. However, the system struggled to perform effectively in drought conditions. The authors recommend exploring solutions that improve water efficiency further, even under extreme conditions, to maximize sustainability and resource conservation in various climates.

K. Rahman et al. [15] utilized predictive analytics to optimize hydroponic nutrient delivery, resulting in a 20% growth improvement. The system was designed to manage data securely; however, data security remains an area requiring improvement, particularly in sensitive agricultural settings. The authors propose enhancing encryption protocols to protect data integrity while maintaining system efficiency.

A. Gupta et al. [16] explored the use of genetic algorithms in IoT-based hydroponic systems to optimize nutrient levels, improving crop yields while minimizing resource use. The system used a network of sensors to collect data on environmental factors such as pH, temperature, and nutrient concentration, which was then analyzed by a genetic algorithm. This approach led to a 25% increase in crop yield due to more precise nutrient dosing, making the system more efficient than traditional methods. However, the genetic algorithm's high computational demand was a limitation, particularly for IoT devices with limited processing power. The study suggested further optimization of genetic algorithms for low-power IoT applications, enabling their use in small-scale hydroponic setups without sacrificing performance. The researchers also recommended exploring alternative optimization techniques to reduce the system's computational requirements, making it more suitable for energy-efficient, IoT-enabled hydroponic systems that are both effective and accessible for broader adoption.

J. Lin et al. [17] designed a hydroponic system incorporating IoT for remote control and data logging, significantly reducing manual oversight requirements. The system featured a mobile app interface that allowed users to access real-time data and remotely adjust environmental settings. The researchers reported a 50% reduction in manual labor associated with hydroponic maintenance, attributing this improvement to the real-time control provided by the IoT-based system. Data logging capabilities enabled users to track historical trends in environmental variables, further enhancing the system's utility. However, the authors identified a gap in the system's long-term reliability, as it had only been tested over short periods. They recommended extending the duration of system trials to evaluate durability and stability under varying conditions, ensuring sustained efficiency for hydroponic farms. Future work could explore enhanced remote diagnostic features to improve system resilience, reducing the likelihood of performance degradation over time.

C. Baker et al. [18] investigated the application of IoT sensor networks in multi-crop hydroponic systems, focusing on optimizing resource use for different plant species. The system employed multiple sensors to monitor environmental factors such as temperature, humidity, and nutrient levels, which varied across the different crop zones. The researchers observed a 15% improvement in water and nutrient use efficiency due to the precise adjustments enabled by the sensor network. However, compatibility issues between sensors from various manufacturers limited the system's overall performance, creating challenges in integrating a unified control system. The study emphasized the need for standardized protocols to ensure seamless sensor integration, particularly in diverse crop settings. Future research was recommended to focus on developing adaptable sensor networks that can manage multiple crop requirements simultaneously, maximizing the efficiency and scalability of multi-crop IoT-based hydroponic systems for broader agricultural applications.

F. Chen et al. [19] presented a low-cost IoT hydroponic solution for small-scale farming, achieving notable cost reductions while maintaining essential functionalities for effective hydroponic management. The system reduced overall costs by approximately 30% by using affordable sensors and microcontrollers, making it accessible to small-scale growers who might be unable to afford high-end equipment. The system monitored critical parameters such as pH, temperature, and nutrient levels, providing users with real-time data through a mobile app interface. However, scalability emerged as a limitation, as the system's design was tailored for small setups and was insufficient for large-scale operations. The authors recommended further research to develop cost-effective scalability solutions, enabling the system to expand to commercial agriculture without compromising performance. This could involve modular designs or enhanced data processing capabilities that maintain efficiency across larger setups, making low-cost IoT solutions viable for a broader range of hydroponic applications.

H. Lee et al. [20] proposed a hybrid IoT-based system that integrates hydroponics with aquaponics, aiming to enhance sustainability by utilizing fish waste as a plant nutrient source. This approach resulted in a 20% improvement in resource sustainability due to the closed-loop nature of the system, which reduced the need for artificial nutrients. The researchers reported that the system effectively maintained optimal growing conditions while minimizing environmental impact. However, the study's limitation was its lack of extended testing, as it had only been evaluated under controlled conditions for a limited period. The authors recommended conducting longitudinal studies to assess the system's effectiveness across different seasons and environmental conditions, addressing variability in nutrient availability and water quality. Future work could also explore integrating advanced IoT analytics for real-time plant and fish health monitoring, improving the system's resilience and ensuring consistent performance.

P. Smith et al. [21] developed a multi-layer IoT-based nutrient delivery system for hydroponics, achieving better nutrient absorption in plant roots through controlled dosing at different stages of growth. The system utilized a network of sensors and microcontrollers to deliver nutrients in layers, optimizing the timing and concentration of nutrients for different growth phases. This multi-layer approach improved root health and resulted in a significant increase in plant yield. However, due to the complexity and cost of managing multiple nutrient delivery points, the study was limited by its inability to scale efficiently for larger farms. The researchers suggested that future work could focus on simplifying the multi-layer delivery method for scalable applications, possibly through automation techniques that reduce the need for manual configuration, making the system viable for larger-scale hydroponic operations.

R. Yamamoto et al. [22] explored IoT combined with image processing to monitor plant health in hydroponic systems. Their system included high-resolution cameras and IoT sensors to capture data on plant growth, enabling early detection of issues like nutrient deficiencies and pest infestations. The researchers achieved a 92% accuracy rate in identifying plant health conditions, significantly improving the timeliness of interventions. However, the reliance on high-quality imaging hardware was noted as a limitation, as the system's effectiveness decreased with lower-resolution cameras. They suggested further exploration of low-cost imaging solutions that could offer similar accuracy levels, making this approach more accessible and sustainable for a broader range of growers, especially in regions where high-quality equipment is cost-prohibitive.

S. Liu et al. [23] proposed an IoT hydroponic system integrated with blockchain technology for secure data sharing, addressing privacy concerns in agriculture. The system used a combination of sensors and blockchain protocols to monitor and securely log environmental conditions, ensuring that data was accessible only to authorized users. Results indicated that blockchain integration effectively enhanced data security, fostering trust in shared agricultural data. However, the system's high energy consumption due to continuous blockchain transactions was a drawback. The authors recommended future studies to develop low-energy blockchain protocols or alternative secure data management systems. This allows for secure yet energy-efficient IoT solutions in hydroponics that protect user data without compromising system sustainability.

T. Brown et al. [24] implemented a cloud-integrated IoT system in hydroponics for environmental control, utilizing real-time data analytics to optimize plant growth conditions. The cloud-based architecture allowed for remote monitoring and adjustments, enabling a 15% increase in yield by maintaining consistent environmental conditions. However, the system's dependency on stable internet connectivity was a limitation, especially for rural applications with intermittent connectivity. The researchers suggested incorporating offline functionality to improve the system's robustness, allowing it to continue operation during connectivity lapses. They recommended future work to explore hybrid cloud-edge computing approaches, balancing centralized data processing with localized control and providing a reliable solution for hydroponic growers in areas with unreliable internet access.

Q. Zhang et al. [25] designed an IoT hydroponic system with real-time data processing for precise nutrient dosing, achieving a 20% improvement in resource efficiency. The system utilized a feedback loop to adjust nutrient levels based on real-time sensor readings, minimizing waste and ensuring optimal conditions for plant growth. However, the study identified a gap in environmental adaptability, as the system struggled under diverse climate conditions. The authors recommended testing the system in a broader range of environments to evaluate its versatility and resilience. They also suggested developing adaptive algorithms that account for fluctuating external factors, enhancing the system's applicability in varied geographic and climatic conditions, thereby making it suitable for global deployment in hydroponic farming.

## III. SUMMARY OF THE LITERATURE SURVEY

This section compiles and synthesizes core findings from recent research on haze removal, emphasizing notable advancements and ongoing challenges in the field. As haze substantially degrades visual clarity and image quality across various applications, researchers have investigated multiple methodologies—from conventional methods like dark channel prior and color attenuation to advanced deep learning models—to improve haze removal accuracy and efficiency. This review systematically evaluates these techniques, focusing on the effectiveness, adaptability, and limitations of traditional and AI-based approaches, offering a comprehensive overview of haze removal methods' progress and current state.

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Table 1: Summary of the Literature Survey

| Sr. No. | YOP | Title and Name of Author | Main Findings | Methodology | Limitations | Application |
|---|---|---|---|---|---|---|
| 1 | 2018 | J. Smith, et al. | The IoT-based hydroponic system enhances plant yield by 25%. | Arduino-based setup with real-time control via mobile app. | Precision agriculture | 1 |
| 2 | 2018 | R. Johnson, et al. | 30% reduction in manual intervention with cloud-based monitoring. | ESP32 with cloud database for real-time analytics. | Remote crop management | 2 |
| 3 | 2019 | A. Lee, et al. | 20% improvement in water efficiency with a closed-loop system. | Raspberry Pi-based system with nutrient control. | Commercial hydroponics | 3 |
| 4 | 2019 | M. Williams, et al. | 15% higher yield using data-driven nutrient optimization. | Machine learning model for nutrient adjustment. | Resource management in agriculture | 4 |
| 5 | 2020 | L. Garcia, et al. | 10% reduction in nutrient overuse through IoT integration. | Cloud-linked nutrient dosing system. | Sustainable farming | 5 |
| 6 | 2020 | S. Patel et al. | 20% decrease in water usage with an analytics system. | ESP32 microcontroller with real-time monitoring. | Water conservation in agriculture | 6 |
| 7 | 2021 | H. Chen et al. | 30% improvement in monitoring accuracy via sensor fusion. | Combined environmental sensors for precise data. | Multi-crop farming | 7 |
| 8 | 2021 | T. Nguyen et al. | A 15% yield increase is due to the ease of mobile-based monitoring. | Mobile app for real-time system control. | Small-scale hydroponics | 8 |
| 9 | 2022 | P. Kumar et al. | 12% growth efficiency improvement using AI analytics. | AI-based nutrient control for precision dosing. | Rural hydroponic setups | 9 |
| 10 | 2022 | M. Alvarez et al. | 30% cost reduction achieved with affordable IoT setup. | Low-cost hardware for small-scale farms. | Home farming | 10 |
| 11 | 2022 | D. Singh et al. | Automated pH management reduces manual work by 40%. | Feedback-controlled automated pH dosing. | Precision agriculture | 11 |
| 12 | 2022 | N. Sharma et al. | 10% energy saving with solar power integration. | Solar-powered IoT hydroponic system. | Green farming | 12 |
| 13 | 2022 | R. Wang, et al. | 95% accuracy in nutrient prediction with deep learning. | The deep learning model for nutrient prediction. | High-tech farming | 13 |
| 14 | 2023 | F. Ochoa et al. | 15% water savings achieved through predictive AI models. | AI-based water use prediction in IoT system. | Water-scarce regions | 14 |
| 15 | 2023 | K. Rahman et al. | 20% growth improvement with predictive nutrient | Secure IoT setup with predictive data | Data-driven farming | 15 |

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|---|---|---|---|---|---|---|
| | | | analytics. | analytics. | | |
| 16 | 2023 | A. Gupta et al. | 25% yield increase using genetic algorithms for optimization. | Genetic algorithms for nutrient dosing. | Cost-efficient farming | 16 |
| 17 | 2023 | J. Lin, et al. | 50% manual oversight reduction via remote control. | Data logging with remote control features. | Labor-saving farming | 17 |
| 18 | 2023 | C. Baker et al. | 15% resource efficiency gain in multi-crop hydroponics. | IoT sensor network for multi-crop monitoring. | Multi-crop agriculture | 18 |
| 19 | 2023 | F. Chen et al. | 30% cost reduction for small-scale setups. | Low-cost hardware IoT system. | Affordable hydroponics | 19 |
| 20 | 2023 | H. Lee et al. | 20% sustainability gain using an aquaponics hybrid system. | Hybrid hydroponics-aquaponics system. | Eco-friendly farming | 20 |
| 21 | 2023 | P. Smith, et al. | Enhanced root absorption through multi-layer nutrient delivery. | IoT-controlled multi-layer nutrient system. | Commercial farming | 21 |
| 22 | 2023 | R. Yamamoto et al. | 92% accuracy in plant health detection with imaging. | High-resolution imaging with IoT sensors. | Plant health monitoring | 22 |
| 23 | 2023 | S. Liu et al. | Improved data security through blockchain integration. | Blockchain-enabled IoT hydroponic system. | Secure data management | 23 |
| 24 | 2024 | T. Brown, et al. | 15% yield increase with cloud-integrated environmental control. | Real-time data analytics via cloud. | Remote management | 24 |
| 25 | 2024 | Q. Zhang et al. | 20% resource efficiency gain through feedback nutrient control. | Feedback loop for real-time nutrient dosing. | Global hydroponics | 25 |

## IV. DISCUSSION

The review of IoT-based hydroponic systems highlights the transformative impact of integrating advanced technology in agriculture, with significant gains in efficiency, resource management, and scalability. One of the most notable advancements is real-time monitoring and control mechanisms, which enable farmers to manage hydroponic systems remotely and make informed decisions based on live data. Studies consistently report improvements in crop yield, water efficiency, and nutrient management due to precision control made possible by IoT devices. These findings underscore the potential of IoT to revolutionize hydroponics by reducing dependency on manual oversight and enhancing productivity through automated adjustments. The technology allows for fine-tuning environmental factors like pH, temperature, and humidity, which are crucial for optimal plant growth, thus establishing IoT as a valuable tool for achieving sustainable agriculture.

With the advent of deep learning, Convolutional Neural Despite these advancements, the literature also reveals persistent challenges, particularly in scalability, energy consumption, and data security. For instance, several studies indicate that while small-scale systems achieve high efficiency with IoT integration, scaling these systems for more extensive commercial operations introduces data management, sensor compatibility, and power requirements complexities. Energy-efficient designs ensure these systems operate sustainably, especially in remote or off-grid locations. Data security is another critical area, as IoT-based hydroponic systems collect vast amounts of sensitive agricultural data. Secure protocols like blockchain can enhance data protection, but their high energy consumption presents a challenge. Addressing these issues requires a balanced approach that includes energy optimization, standardization of IoT components, and secure, low-power data management solutions.

The ongoing development of machine learning and artificial intelligence (AI) algorithms in conjunction with IoT for hydroponics is a promising area that could further optimize resource use and crop yields. By employing predictive analytics, IoT systems can anticipate changes in environmental needs and make preemptive adjustments, reducing waste and enhancing growth conditions. However, as the literature suggests, these advanced systems face limitations, including dependency on robust internet connectivity, which can be unreliable in rural areas. Developing hybrid solutions that combine cloud-based analysis with localized processing could improve resilience in regions with connectivity issues. Future research should also explore adaptive IoT systems that account for diverse environmental conditions, enabling a more universal application of hydroponic technology. These advancements can make IoT-based hydroponics more accessible, sustainable, and effective globally.

## V. CONCLUSION AND FUTURE SCOPE

Integrating IoT technology in hydroponic systems marks a substantial advancement in precision agriculture, optimizing plant growth conditions, reducing resource wastage, and allowing for remote, automated management. The reviewed studies indicate that IoT-based hydroponics can significantly enhance crop yield, water, and nutrient efficiency, making these systems valuable for sustainable agriculture. IoT provides the flexibility and control necessary for maintaining ideal plant health, even in controlled environments, by enabling real-time adjustments to environmental conditions. However, the studies also highlight limitations such as scalability, energy consumption, and data security challenges that must be addressed to ensure reliable, large-scale applications.

Future research and development should focus on designing energy-efficient IoT systems to reduce power requirements, especially for off-grid or remote hydroponic setups. Further, integrating secure, low-energy data management solutions like optimized blockchain or alternative encryption methods could provide enhanced data security without compromising energy efficiency. Another promising area for future work is the application of AI and machine learning algorithms to improve predictive capabilities, allowing IoT systems to forecast plant needs and autonomously adjust conditions. Hybrid systems that combine cloud and edge computing could also help address connectivity challenges in rural areas, offering a robust solution for regions with limited internet access.

As these technologies evolve, the potential exists for IoT-based hydroponic systems to become more adaptable and accessible worldwide. Future IoT designs that can accommodate multi-crop systems and diverse environmental conditions will be particularly valuable for expanding the use of hydroponics across different agricultural contexts. By addressing these challenges, IoT-driven hydroponic systems can play a pivotal role in advancing sustainable, resource-efficient agriculture, supporting food security, and promoting environmentally friendly farming practices on a global scale.

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