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A Review of IoT-Enhanced Sustainable Farming: Integrating Aquaponics, Hydroponics, and Poultry for Future Agriculture

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Peer Review Information	Abstract
<i>Submission: 19 Jan 2025</i> <i>Revision: 21 Feb 2025</i> <i>Acceptance: 25 March 2025</i> Keywords <i>Aquaponics</i> <i>Hydroponics</i> <i>Poultry Integration</i> <i>Sustainable Agriculture</i> <i>Resource Efficiency</i> <i>Real-time Monitoring</i> <i>Automation</i>	This paper reviews the integration of aquaponics, hydroponics, and poultry farming systems, all of which have been improved with IoT and AI technologies to form a scalable, resource-efficient, and self-sustaining agricultural ecosystem. IoT-enabled sensors and automation achieve the optimized use of water, nutrient cycling, and environmental conditions. These systems have drastically reduced the consumption of resources and wastes. This is where aquaponics brings fish farming together with hydroponics. Fish excreta serves as a natural fertilizer for plants, while hydroponics allows for soil-free cultivation, making it suitable for water-constrained and urban areas. Including poultry farming in this concept further supports this closed-loop model by supplying organic wastes, recycling nutrients, and reducing reliance on synthetic fertilizers. This review discusses advances in technology, the advantages and disadvantages of each system, a comparison of adaptability to various environments, and the determination of salabilities. It further unfolds active and ongoing research gaps, such as finding low-cost, energy-efficient components and modular system design, and suggests pathways to future research in sustainable agriculture. The findings open up the huge potential of IoT in transforming agriculture toward a highyield and sustainable food production system that will effectively address pressing food security and environmental concerns.

INTRODUCTION

The challenge in this context arises because of an unprecedented rise in the world population, intensifying food demand in conventional agriculture. Thus, issues related to arable land shortage, scarcity of water resources, and deterioration of environmental conditions raise

concerns about finding immediate sustainable alternatives for such traditional systems of agriculture. They tend to be mainly monoculture, with large-scale chemical inputs and resource consumption, leading to long-term effects such as soil degradation, biodiversity loss, and carbon emissions. Researchers seek to study new ways of

agriculture by focusing on their production, sustainability, and resource efficiency [1].

An integrated alternative is the farming system of aquaponics, hydroponics, and poultry farming integrated into one single system. It embraces the culture of plants, fish, and poultry in a controlled closed-loop methodology, the purpose of which is to be able to minimize input coming from the outside environment and thereby maximize circular resource utilization. Such systems, fusing the technologies of the Internet of Things with automation, allow for monitoring and alteration of factors in the environment in real-time to facilitate efficiency, eliminate waste, and enhance productivity. In that regard, integrated farming systems are now in research and, therefore, topics like food security, water, and agricultural sustainability have become relevant areas of concern; hence, the subject is relevant to the current scenario [2].

Current Challenges in Traditional Farming

Growing pressure from environmental, economic, and social factors makes traditional farming methods incapable of supplying the growing world population's needs. Some of the major issues are lack of arable land, less availability of water, loss of soil quality, and effects of pesticides on the ecological system. Industrial agriculture by monoculture and criminalization has caused a lot of environmental problems, including a loss of biodiversity, reduction in soil quality, and increased greenhouse gas emissions. These variables bring down the resilience of food production and thus render it ever more vulnerable to climatic variability and catastrophic weather phenomena [3].

Traditional farming mostly relies on water, accounting for 70% of the entire global water usage. Still, the misuse of water consumption leads to waste while irrigation that is excessive causes salinization and nutrient leaching, where soil deteriorates over time. It also poses an environmental and human health threat by poisoning the water bodies, adverse impacts of such chemicals on species beneficial for the farmers' production, and a rapid rate of soil pollution [4].

Necessity for Integrated Systems

Considering these pressing issues, integrated agricultural systems such as aquaponics, hydroponics, and poultry are among the viable alternatives. These systems represent the concepts of cyclical resource use and sustainable agriculture, creating a self-regulating system where plant, animal, and fish production coexist harmoniously. Integrated systems effectively reduce the need for external inputs by using

waste from one component as input for another, thereby maximizing resource use [5].

- Aquaponics is the integration of aquaculture and hydroponics in a closed-loop system. The excretion from fish serves as organic nutrients for the development of plants, while plants have the natural ability to filter and purify the water for recirculation into the fish tanks. This device reduces water consumption by circulating the water within, making it ideal for areas that experience water constraints [6].
- Hydroponics allows for growing plants without soil by using nutrient-rich, aqueous solution. It provides an opportunity to regulate nutrients effectively, thus increasing the rapid growth of plants, greater yields, and the optimal usage of resources. Its versatility also makes it possible for usage in urban and rural places to ensure sustainable food production in non-arable regions [7].
- Poultry integration enhances the systems by providing supplementary organic waste, which is a nutrition source for the culture of plants and fish. With this closed-loop methodology, reliance on artificial fertilizers is reduced and soil integrity is preserved, promoting a balance in the ecosystem, enhancement of biodiversity, and therefore productivity [8].

The Role of Technology

IoT-enabled automation and real-time monitoring functions improve the productivity of the integrated farming system. Environmental sensors such as ESP32 microcontrollers monitor temperature, humidity, pH, and nutrient levels and can easily be changed to create a better environment. Using IoT for the automation of irrigation, distribution of nutrients, and control of climate will ensure quality output uniformity because the labor requirement and the scope for errors are decreased by this whole process. Accuracy at this level is complemented by algorithms employed for machine learning during data analysis and crop requirements can be well predicted in advance, alongside hazards that may be curtailed, for improvement in the sustainability and resilience of agriculture [9].

Integration of IoT with integrated farming systems is the most revolutionary approach to modern agriculture. Such systems effectively address the prime concerns related to food security, environmental sustainability, and resource efficiency. In that regard, the innovations and discoveries through such technologies have exceeded all limitations that

traditional agriculture imposed, and scalable solutions can be applied in almost any environment, from rural farmlands to urban rooftops [10].

Scope and Objectives

This paper reviews the recent developments in IoT-enabled integrated farming systems. It provides insight into the progress made and research on hydroponics, aquaponics, and poultry integration. The technical advancements reviewed include the integration of sensors, automation, and data analytics for enhanced efficiency and sustainability [11].

The objectives focus on the synthesis of existing approaches, analysis of the solutions available, research gaps like scalability and energy consumption, and suggestion of future research paths. Overall, this survey is broad and divided into sections about each of the system components, which enables a comparative analysis, discussing challenges faced, and recommending the way to sustainable agriculture [12].

LITERATURE SURVEY

The integration of IoT and AI technologies in agriculture has brought about the most drastic transformation in traditional farming, particularly in hydroponics and aquaponics. Resource usage is optimized with the help of advanced sensors, crop yields are improved, and environmental sustainability is promoted through data analytics. This literature review will discuss several works that have been developed and applied in the areas of hydroponic and aquaponic farming using IoT-based systems, focusing on contributions toward water conservation, automation, and real-time monitoring. This survey attempts to give insight into the possibilities of intelligent agricultural technologies toward changing the future of farming by exploring challenges, advancements, and research gaps identified in these works [13].

Hydroponics System

Hydroponics is a revolutionary method of growing plants without soil by utilizing nutrient-rich water solutions. This innovative agricultural approach offers significant advantages, including efficient resource utilization, accelerated plant growth, and the ability to cultivate crops in nonarable regions. With the integration of Internet of Things (IoT) technologies, hydroponic systems have evolved into smart agricultural solutions that enable real-time monitoring and automation of environmental conditions such as temperature, humidity, light, and nutrient levels. The sample model of hydroponic farming is present in Fig.1.



Fig.1. Hydroponic Farming [14]

Pola Anirudh et al. (2023) [15] proposed an IoT-based hydroponic system that can automate the indoor agriculture system in multiple ways. The concept incorporates sensors such as DHT11 for temperature and humidity, LDR for light detection, water level sensors to enhance the supply of water, and artificial sunshine for the development of plants. The technology constantly collects and analyzes environmental data, self-regulating parameters like light intensity and irrigation schedules, so it keeps the conditions ideal for plant development. Thus, this method increases the efficiency of resource utilization and reduces physical labor, making it more reasonable for domestic hydroponic farming. The authors have designed an intuitive smartphone application that allows remote monitoring and control of the system; it has the provision of real-time alerts and analytics of the data collected. Such connectivity will make it more convenient for urban gardeners to contribute more to sustainable farming practices. This research highlights the potential of IoT technologies to transform indoor agriculture through improvements in resource efficiency and augmented crop yields.

Sairam Nadipalli et al. 2021 [16] placed more emphasis on water-saving via designing an IoT-based smart metering solution in hydroponic systems. Their effort in maximizing the effectiveness of water involves automated irrigation through its system, ensuring time and proper delivery of water with real-time data. The parameters such as moisture content, temperature, and humidity are measured by several sensors used in a smart meter, which allows the control of irrigation to be changed in real-time. This sensor-integrated platform through a cloud provides access from remote locations for the user to make informed decisions about water consumption. The machine learning algorithms check the data available in history; some predictions regarding future requirements are made, and the irrigation schedule is adjusted accordingly. This reduces water wastage and increases crop yield and quality. The researchers conducted experiments to validate the system. They showed that there was a significant reduction in water usage compared to other traditional irrigation systems. Their research is

one of the contributions to sustainable agriculture techniques innovations by focusing on the role of technology in solving water scarcity issues in hydroponics.

Venkatraman M and Surendran R (2023) [17] Designed and implemented an advanced hydroponics farming system using nutrient film technology for the cultivation of lettuce. The study utilizes IoT technologies and automation for monitoring and controlling environmental conditions such as temperature, humidity, pH, and light intensity. The proposed device uses microcontrollers and sensors to provide maximum uptake of fertilizers and oxygen by flowing nutrient-enriched water over the roots of plants. The study used neural networks for the identification of problems, and hence it was a promising substitute for urban agriculture and cases where traditional farming is impossible. This approach has vast potential in sustainable agriculture, especially in resource-scarce regions.

S. Qazi et al. (2022) [18] Presented a comprehensive review of novel agricultural systems integrated with IoT and AI, focusing on future trends in optimizing farming through automation and predictive algorithms. Their research emphasizes the need for integrating AI-driven models for instant decision-making in complex agricultural environments, such as hydroponics. The authors advocate for intelligent systems that can analyze enormous amounts of data to promote efficient and productive agricultural practices through many case studies and technologies. This review is thus an exhaustive guide for researchers and practitioners looking to put into practice intelligent agricultural technologies, outlining challenges and future solutions.

K.A. Ogudo et al. (2023) [19] Developed an AI-based autonomous system for skin lesion detection, using optimal methods to improve the accuracy of classification. Although the context is different, the same AI methods can be applied in hydroponic systems for anomaly detection, thereby allowing for timely interventions in crop management. Using complex machine-learning techniques similar to those used in medical diagnosis, hydroponic systems can potentially identify issues like nutrient deficiency or plant disease outbreaks. It calls across various disciplines and showcases flexibility in AI technologies with implications that health insights in agri can be optimized further, improving crop watch as well as a management approach. There have been significant steps that the incorporation of AI into the farmland presents toward achieving adaptable or resilient farming systems.

Lakshmi Sudha Kondaka et al. (2023) [20] proposed a Smart Hydroponic Farming System that uses machine learning approaches to

automate various aspects of indoor farming. Their system includes sensors, such as the DHT11 for temperature and humidity, EC sensors for controlling nutrients, and a web application for real-time monitoring and control. This system uses a combination of Deep-Water Culture and Nutrient Film Technique, which is used to boost growth. The system utilizes the machine learning model to regulate autonomic environmental factors for other crops without human intervention, thereby minimizing man's interference and optimizing the usage of resources, hence a feasible alternative for urban and domestic agriculture.

V. Bhatnagar et al. (2022) [21] Informed upon the concept "Sustainable Development in Agriculture: Past and Present Scenario of Indian Agriculture," where the emphasis was placed on the basic need for a platform to grow IoT, that is IoE or Internet of Everything. Their research necessitates enhanced soil sensors as a necessity for effective conditions monitoring. The sensors, in addition to providing key data about soil moisture levels, temperature, and nutrients, send realtime information to the farmers. This method greatly reduces labor and energy consumption. However, the technique has several shortcomings, especially in the efficient calculation of the component heat index, which is vital for accurate crop growth monitoring, thus diminishing the prospects for precision agriculture.

N. G. Rezk et al. (2021) [22] offered an IoT-driven smart agriculture system for water conservation in South Africa. The technology employs machine learning algorithms to control water resources autonomously, thereby ensuring optimal water usage under different agricultural conditions. The approach reduced water loss effectively; however, challenges like limited data transfer range and inefficiencies in present usage prevailed. These limitations affected the scalability and full automation of the system, especially in large-scale agricultural applications. The sediment and water analysis modules that are part of the system provide necessary information for irrigation management; however, more improvements were required to maximize its overall performance.

Z. Khan et al. (2021) [23] Designed an IoT-driven smart agricultural monitoring system that aims to avoid bolting in the production of onions. Their work has been designed using artificial intelligence-based approaches in forecasting nitrogen levels in wheat crops based on the actual photographs taken under varied light conditions and sampling scenarios. This system used image analysis to present relevant information about crop vigor and nutrient requirements. This significantly improved the accuracy of the predicted nitrogen but required considerable

amounts of electricity since the process operated in real time. A high-quality photograph was not readily available in some poor-resource environments, which also created problematic illumination conditions.

I. L. Maldonado et al. (2021) [24] developed an automated hydroponic plant growth system utilizing the ESP32 microcontroller to control various sensors and actuators. It monitors environmental parameters like humidity, temperature, and water levels through the LOTUS app, which is capable of monitoring the real-time growth of plants from germination to harvest. However, the high computational cost resulted in limited deployment of this system. The authors suggested that future refinements, including more efficient computing solutions and further tweaking of the nutrient delivery mechanism, could address these issues, increasing the accessibility and scalability of both small and large-scale hydroponic farming. Maintain Specification Integrity.

Aquaponics System

Takrouni Hedfi Asma et al. (2023) [25] propose an innovative system in aquaponics, bringing fish farming and hydroponics together to develop a solution in agriculture. Their designed system, which revolves around an Arduino Mega board, utilizes the deployment of several sensors measuring pH, water temperature, and water levels. The IoT-based system guarantees the efficient usage of water while minimizing chemical inputs required in plant cultivation. Aquaculture and hydroponics are combined to allow the continuous reuse of water, therefore creating a selfregulating, closed-loop environment for both fish and plant growth. The authors prove the system's practicality, especially in water-scarce regions like southern Tunisia. Their system effectively automates the regulation of critical parameters, but the study still suggests improvements in the future, which include the integration of automated greenhouse control to optimize plant growth.

Purushottam Kumar et al. (2023) [26] used machine learning for fish weight growth prediction in aquaponics systems. Here, the authors have implemented regression algorithms like linear regression, lasso regression, ridge regression, KNN regression, SVR, and decision tree regression. Here, the data is being extracted from the aquaponic fish pond with the help of IoT sensors for temperature, ammonia, dissolved oxygen, and turbidity. For those using feature selections, KNN produced more accuracy, with 99.15% prediction while tree regressions offered around 99.1%. Such results show the importance and benefit of incorporating machine learning models in aquaponic farming for optimal fish yield alongside optimum nutrient levels. One

aspect of future work on such systems would be their consideration involving sophisticated deep-learning models into existing architecture for large-scale improvement in the system.

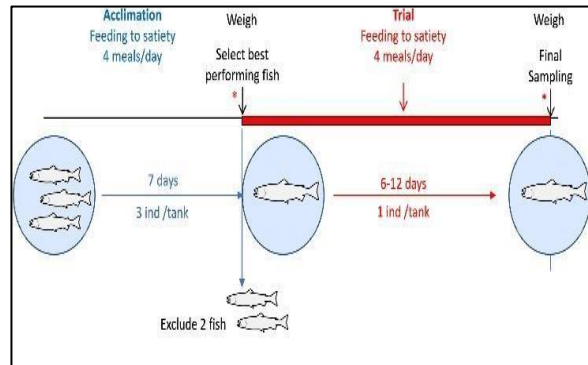


Fig.2. Estimate Fish Weight Growth [27]

Munnangi Sree Chandana et al. (2023) [28] designed an automated aquaponics farming system based on IoT technology. The system combines a pH sensor, ultrasonic sensor, and DHT11 sensor, interfaced with the NodeMCU microcontroller, for the monitoring and control of the parameters in the system. This system will allow precise time-based monitoring of essential environmental parameters, such as pH, humidity, temperature, and water levels. The system is also able to automate the feeding of fish using a servo motor.

Even though the system has good monitoring and management efficiency, scalability issues can be considered problematic due to its reliance on particular hardware components and lack of processing power. Some recommendations for future use may include the optimization of the system to be utilized for larger farming operations in terms of enhancing data processing capabilities and energy efficiency. Some more sophisticated sensors should be incorporated into the system, as well as some adjustments to the control algorithms.

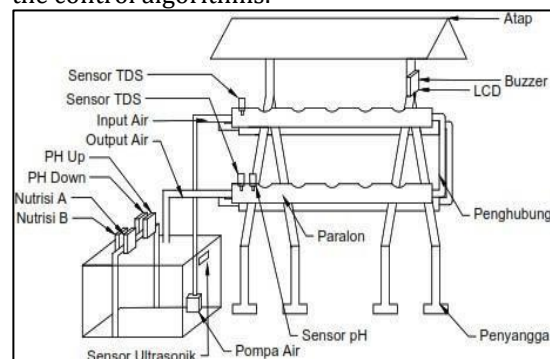


Fig.3. Aquaponic System [29]

C. S. Arvind et al. (2022) [30] The work concentrated on the regulation and control of environmental parameters such as temperature, humidity, and water quality in an IoT-based aquaponics system. The authors made a working prototype that senses and controls the parameters through actuators. By controlling

environmental factors automatically, the proposed prototype showed great potential in greatly improving the efficiency of aquaponics farming. It enhances yield and reduces fish mortality by providing real-time monitoring and adjustments. The study underlines the benefits of IoT integration for the creation of a more sustainable and efficient aquaponics system.

Poultry System

T. Malini et al. (2023) [31] designed an IoT-based innovative poultry farm monitoring system to improve poultry health and productivity by allowing remote monitoring and control. The system integrates sensors using an Arduino Nano and transmits data to the cloud using an ESP32 Wi-Fi module. The critical environmental parameters of temperature, ammonia levels, and light intensity are continuously monitored, thus enabling effective management by farmers. This will greatly reduce the monitoring by manual check-ups, allowing data to be accessed via mobile devices in real time. The authors explain that this modern agriculture solution can revolutionize poultry health and productivity significantly because it eliminates common drawbacks inherent in traditional agriculture practices. Future improvements might be the integration of advanced algorithms on machine learning for predictive analytics that may further optimize the operation of farms and enhance the process of decision-making.

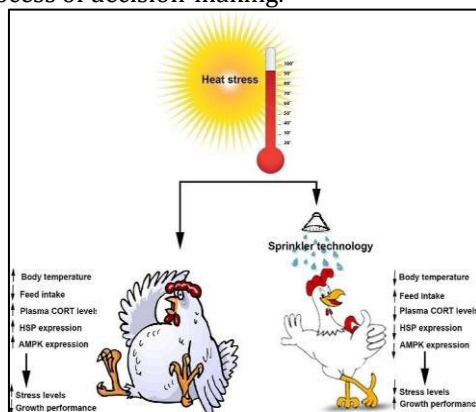


Fig.4. Poultry System [32]

Sandesh Phadtare et al. [33] analyzed automation dictation in the light of quality improvement in substance manufacturing concerning the impact on the balance of resource provision. The study is necessary to introduce advanced technologies for improving agricultural practice's efficiency. The authors have pointed out the significance of bird management systems, which apply IoT devices for monitoring critical environmental parameters such as temperature, humidity, light intensity, and air quality. With its low-cost hardware and open-source programming, the automation-based approach will achieve broad acceptability. Thus, implementing such systems for this research will

solve other poultry management-related problems such as improving the conditions to further promote growth and welfare concerns in animal agriculture. Based on the current findings, integration with automation and IoT would easily solve most existing problems while improving the productivity and sustainability of agricultural operations. This research contributes valuable insights into the potential of intelligent technologies to revolutionize substance manufacturing and promote better resource management practices in the farming sector.

Hambali et al. [34] designed a dictation system that monitors and maintains a healthy environment in poultry farms through the monitoring of critical environmental parameters, such as temperature, humidity, ammonia levels, and water stability. The paper outlines the application of automation in optimizing hen management through a wireless sensor network and a mobile communication system. This approach gives real-time monitoring and automatic regulation of critical poultry health factors. This will ensure that the chickens are raised in the most favorable settings due to automation of the environmental condition control, which minimizes stress and leads to better growth and productivity. The authors say their automated solution monitors all these parameters continuously and dynamically responds to any fluctuation compared to traditional methods. Such intelligent systems can greatly improve animal welfare and operational efficiency, thus making the technology a very vital tool for modern poultry farming practices.

M. Rahman et al. (2023) [35] designed an IoT-based smart farming automation system for the enhancement of the productivity of a poultry farm by monitoring the environment accurately and automating tasks. The system utilizes an ESP32 microcontroller to control sensors monitoring temperature, humidity, rainfall, and food levels. Automation of the critical functions in the farm includes dispensing food and water and deploying the rain-protective curtain. The study further includes a mobile and web application for remote access with real-time data and alerts on environmental anomalies and resource shortages. Data-driven approaches allow farmers to make timely adjustments, which means optimizing animal welfare and labor. The authors report great improvements in farm management efficiency as the system reduces manual intervention but maintains optimal conditions for poultry. Future directions proposed include improvement in biogas production from poultry wastes and integration of automated theft detection to further extend the capacities and sustainability of the system in poultry farming environments.

Sharan Kumar et al. (2023) [36] proposed an IoT-based automated poultry farm system, especially for layer chickens using artificial intelligence techniques to achieve improved productivity and health monitoring. It uses a combination of LSTM networks with RF models in the image analysis of chickens to get 95% detection accuracy in age classification. This model helps in real-time health monitoring of chickens, detects early disease, and thus leads to better welfare. Another approach they adopted was data augmentation, where they improved the model's performance even though there was an imbalance in their dataset. Their approach therefore explains how advanced AI techniques may feature in modern poultry farming: providing a framework that would integrate IoT for efficient management and decision-making. Future developments could increase the dataset and sharpen the classification algorithms to enhance its accuracy and reliability in various agricultural conditions.

A. M. Elbarrany et al. 2023 [37] designed a computer vision-based system to monitor and analyze abnormal behaviors in poultry farms based on the main issues affecting chicken health and productivity. It uses deep learning techniques for video recording analysis of chickens by breaking the video into 10-second intervals for practical analysis. The researchers were

successful in applying CNNs in recognizing behaviors in chickens that entail eating, sleeping, or abnormalities with an accuracy as high as 96.43%. The early warning system of automated surveillance for stress or illness in chickens will enable farmers to undertake prompt action to enhance animal welfare and improve farming efficiency. This study emphasizes the idea that behavioral analysis is pivotal in maintaining poultry health for sustainable farming practices. The authors continue to propose further improvements, with an expanded dataset and additional incorporation of AI algorithms, enhancing the robustness and applications of the monitoring system in other farming environments.

SYSTEMATIC REVIEW

This section offers a systematic review of the relevant literature on IoT and AI-driven integrated farming systems based on hydroponics, aquaponics, and poultry farming. All these systems have been integrated to get maximum efficiency concerning resources, automation, and sustainability through IoT. The following table provides details on the methodology of each study, its technological approach, and its findings.

Table 1: Systematic review

Sr. No.	Author(s)	Title of the Project	Published Journal Name and Year	Methodology	Technical Aspect	Overview
[1]	Pola Anirudh et al. [14]	IoT-based hydroponic system for indoor agriculture automation	ICACCS, 2023	IoT with sensors and real-time mobile control	Automated control of temperature, humidity, light, and water levels	Efficient indoor farming automation
[2]	L S P Sairam Nadipalli et al. [15]	Water Conservation Control by using IoT Smart Meter	ICCMC, 2021	Automated irrigation with IoT and ML	Predictive water management	Reduces water waste in hydroponics
[3]	Venkatraman M and Surendran R [16]	Smart Hydroponics Farming for Growing Lettuce Plantations under Nutrient Film Technology	ICAAIC, 2023	IoT and neural networks for fault detection	Environmental monitoring for nutrient management	Reliable resource efficiency for urban farming

[4]	S. Qazi et al. [18]	IoT-Equipped and AI-Enabled Smart Agriculture: A Critical Review	IEEE Access, 2022	Review on automation and predictive AI	Real-time decision-making in agriculture	Overview of Smart Agricultural Trends
[5]	K.A. Ogudo et al. [19]	AI-based Automated Skin Lesion Detection Model for Hydroponic Anomaly Detection	Computer Systems Science and Engineering, 2023	AI for anomaly detection	Detects nutrient deficiencies in crops	Crossdisciplinary AI applications in hydroponics
[6]	Lakshmi Sudha Kondaka et al. [20]	Smart Hydroponic Farming System Using Machine Learning	IITCEE, 2023	ML-based automated environment control	Nutrient management with EC sensors	Resource-efficient home farming system

[7]	V. Bhatnagar et al. [21]	Sustainable Development in Agriculture: Past and Present Scenario of Indian Agriculture	IGI Global, 2022	Soil sensors for continuous monitoring	Provides realtime feedback on soil conditions	Supports sustainable soil management
[8]	N.G. Rezk et al. [22]	IoT-Based Smart Farming System for Water Conservation	Multimedia Tools and Applications, 2021	ML-based water management	Automated water conservation	Sustainable water use in agriculture
[9]	Z. Khan et al. [23]	IoT-Based Smart Farming Monitoring System for Bolting Reduction in Onion Farms	Scientific Programming, 2021	Image-based nutrient prediction	Nitrogen prediction for crop health	Optimize nitrogen use in onion farms
[10]	I.L. Maldonado et al. [24]	Hydroponic Automated Plant Growth Analysis System Using ESP32	Journal of Advanced Agricultural Technologies, 2021	ESP32-based mobile monitoring	Monitors plant growth stages	Automated control from seed to harvest

[11]	Takrouni Hedfi Asma et al. [25]	IoT Design and Water Monitoring of an Aquaponic System	SCC, 2023	Sensor-based water reuse	Monitors pH, temperature, and water levels	Efficient resource use in waterscarce regions
[12]	Purushottam Kumar et al. [26]	Fish Weight Growth Estimation in Aquaponics Farming via ML	CONIT, 2023	ML regression models	Nutrient and fish growth prediction	Accurate yield estimation in aquaponics
[13]	Munnangi Sree Chandana et al. [28]	Automated Aquaponics Farming Using IoT	ICEARS, 2023	Sensor monitoring with NodeMCU	Automates environmental and feeding parameters	Precision control for largescale farming
[14]	C.S. Arvind et al. [30]	Smart Aquaponics Monitoring with Edge Computing and IoT	SSCI, 2020	IoT and edge computing for environmental control	Monitors temperature, humidity, and water quality	Edgedriven aquaponics for optimize d yield
[15]	T. Malini et al. [31]	IoT-Based Smart Poultry Farm Monitoring	ICACCS, 2023	ESP32-based environmental monitoring	Controls temperature, ammonia, and light for poultry welfare	Enhances poultry health with automati on
[16]	Sandesh Phadtare et al. [33]	Poultry Farm Control System	IRJET, 2020	IoT devices for bird management	Monitors temperature, humidity, and air quality	Affordabl e poultry automati on solution
[17]	Hambali et al. [34]	IoT-Based Smart Poultry Farm in Brunei	ICOICT, 2020	Wireless network for real-time monitoring	Automatic regulation of poultry conditions	Improves poultry welfare with realtime data
[18]	M. Rahman et al. [35]	Smart Farming Automation System for Poultry Farm Productivity Enhancement	ICCIT, 2023	ESP32 and automation for resourc e management	Controls food, water, and environmental conditions	Optimize s lab or and resources in poultry
[19]	Sharan Kumar et al. [36]	AI-Enhanced Poultry Health Monitoring via LSTM and RF	ICAISC, 2023	AI models for image-based age and health monitoring	Classifies age and detects poultry disease	AI-driven welfare monitoring for poultry

[20]	A. M. Elbarrany et al. [37]	Abnormal Behavior Analysis for Poultry Surveillance Using Deep Learning	IMSA, 2023	CNN-based video analysis for behavior monitoring	Detects stress and health anomalies in poultry	Videobased poultry behavior analysis
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RESEARCH GAP

Several research gaps emerge from this systematic review of IoT and AI-driven farming systems that can direct future advances. The most important of these gaps concerns scalability: even though several studies are presented, where IoT seems to hold a high potential for automation and monitoring in hydroponics, aquaponics, and poultry farming, most of the developed solutions have been designed with smaller or controlled environments. There is less research on scalable, cost-effective systems suitable for adoption by larger farms, or applicable in resource-constrained settings. Another major challenge is energy efficiency-the integration of IoT and AI often requires high power sources, which may hinder deployment in remote or otherwise under-resourced areas of operation. Future research can focus on developing low-power devices or incorporating renewable energy sources to reduce operational costs and improve environmental sustainability.

Data quality and real-time adaptability are another area of improvement. For more advanced AI models that are used for anomaly detection and prediction in crop health or poultry behavior monitoring, like LSTM and CNNs, the requirement for high-quality data can be a challenging aspect to maintain. There is a need to develop adaptive models that can work fine despite the issues with variability and quality of data for reliable real-time decision-making. There is also scope for interdisciplinary applications of AI models. For instance, as much as research like [5] shows how AI models coming from other fields, for example, medical diagnostics may be used for agricultural anomaly detection, much more has to be done to try and explore and tailor interdisciplinary AI models specifically tailored for agricultural applications.

The long-term effects and ROI for IoT-based farming systems are an under-researched area. While immediate benefits of efficiency in resource use and productivity are highlighted, research in terms of overall economic impact is scarce, particularly about initial setup costs and the cost of maintenance to the farmers. Moreover, while the aquaponic systems may be efficient in the utilization of water and nutrients, there is scope for dynamic predictive models that would help regulate nutrient levels in real time in response to changes in the environment.

Across all these studies, there's still another thing missing: standardization and protocols. This means diversification in setups for sensors as well as varied techniques applied during monitoring across different research projects. Such operating procedures may help with better consistency and reliability across IoT-enabled farming solutions. Last but not least, edge computing has been proven very effective within an aquaponic system in cutting latency as well as enhancing real-time monitoring as demonstrated in [14]. Further research will be necessary to assess the potential of edge computing in various farming environments that may provide faster data processing and quicker response times. This will fill in many gaps in the research and will greatly improve the field of sustainable, IoT-driven agriculture and its practical applications in various environments.

DISCUSSION

The integration of IoT and AI in agriculture has transformative capacities in various farming systems such as hydroponics, aquaponics, and poultry farming. Since each system has unique features regarding the management of resources, and the ability to automate, scale up, and adapt to natural conditions, it has presented specific challenges that have a potential solution.

Hydroponics

IoT-enabled hydroponic systems, where sensors and data-driven models are used, have maximized resource efficiency by reducing water and nutrient usage to the minimum. Automation in hydroponics reduces dependence on labor and also ensures that conditions for crops are consistent. Hydroponics has been proven through research to thrive in the urban environment and thus will be suitable for sustainable urban agriculture. But despite these systems, there lies a limitation in the scaling up of these systems owing to the high setup cost, in addition to the high amount of energy required, especially by ML models for predictive nutrient management. Future systems shall focus on cost-effective sensor networks and energy-efficient components that reduce operational costs and promote accessibility.

Aquaponics

Aquaponic systems integrate hydroponics with fish farming, and the system is a closed loop where the waste of fish becomes a natural fertilizer for plants. This setup will save a lot of water, making it ideal for water-scarce areas. Although it is only mildly automated, aquaponics may be more resource-friendly at higher levels of automation with IoT sensors and basic machine-learning models for environmental monitoring. However, due to this delicate balance between the aquatic and plant ecosystem, this system has limited scalability. Hence, future work in the field should address developing reliable, low-power hardware compatible with the larger aquaponic setups. Improvement in the predictive models for fish growth and nutrient balancing is a critical support for high-yielding aquaponic systems.

Poultry Farming

IoT and AI technologies in poultry farming continuously monitor the environment, improve the welfare of animals, and increase productivity. Such systems can continuously monitor temperature, humidity, light intensity, and ammonia levels, factors that are directly related to poultry health but with low human interference. Moreover, through AI applications such as CNN and LSTM models, farmers can gain advanced behavior analysis and predictive health monitoring to detect possible health risks beforehand. Although scalable, such systems often rely on high-quality data to be effective for AI models to function correctly, which is difficult to maintain reliably. The challenges addressed need standardized data collection protocols and adaptive AI algorithms that can manage variability in real-world farming conditions.

Comparative Insights

The comparative analysis of the three systems reveals that a balance has been achieved between scalability and complexity. Hydroponic is highly resource-efficient but less scalable. Aquaponics ensures water conservation with great proficiency but demands balanced ecosystem management. Poultry farming ensures scalability along with monitoring but requires very good data quality for proper applications of AI. Each of these systems could help their scalability through modular design approaches such that components could be added according to the size of farms or available resources.

Future Directions

Future agricultural technologies must consider hybrid solutions that encompass elements of each system to optimize efficiency in resource usage, environment sustainability, and scalability. Crossdisciplinary approaches, for example by integrating advanced AI models like those used in

medical diagnostics into agriculture, can produce novel insights that improve all three farming methods' capacity for anomaly detection and predictive maintenance. Further, renewable sources of energy, such as solar power, can be used to reduce the high energy consumption involved in IoT-enabled farming and make the systems more viable for mass-scale deployment.

While IoT and AI have already transformed the ways of agricultural practice significantly, further optimization of agriculture would be likely to be a cost-effective, flexible, and less environmentally destructive direction toward opening up sustainable and resilient farming systems.

CONCLUSION

This survey underlines the transformation potential of IoT and AI technology integration in hydroponics, aquaponics, and poultry farming systems. Every system provides different advantages like increasing the efficiency of resources, scaling, and better monitoring. The challenges, however, lie in the high initial investment required, energy needs, and the need for uniform quality data, thus further development is needed. Future development can overcome these challenges with an emphasis on modular and hybrid systems, along with the integration of renewable energy sources, thus enabling stronger and more sustainable farming methods. With the use of sophisticated technologies, agriculture will be efficient and responsive to the urgent environmental and resource concerns facing the world. Ongoing research and development of these IoT and AI systems can enrich them to adequately satisfy the demand for increasing sustainable food production, thereby ensuring assurance of food security and environmental stewardship.

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