

HydroGrow: A Survey on IoT- and ML-based Intelligent Hydroponic Farming Systems

Akshay M J¹, Pavan M¹, Aishwarya K C², Akanksha H S², Anusha U S², Ashwini G Pai²

¹ Assistant Prof., Department of Information Science and Engineering, Jawaharlal Nehru New College of Engineering, Shivamogga, India

²UG Students, Department of Information Science and Engineering, Jawaharlal Nehru New College of Engineering, Shivamogga, India

Abstract— Hydroponics is increasingly recognized as a sustainable and efficient alternative to conventional soil-based farming, particularly in urban areas constrained by limited land and unpredictable climatic conditions. When integrated with Internet of Things (IoT) technologies, hydroponic systems enable real-time monitoring and precise control of critical parameters such as pH, electrical conductivity, water levels, temperature, and humidity. This fusion of soilless agriculture with controlled environment systems enhances crop productivity, reduces water consumption by up to 80–90%, and minimizes nutrient wastage through data-driven optimization. The use of low-cost sensors, cloud-based platforms, and mobile applications further facilitates remote management, automation, and predictive decision-making, reducing labor demands while improving system reliability. By ensuring healthier plant growth, faster cultivation cycles, and improved resource efficiency, IoT-enabled hydroponic systems demonstrate significant potential to transform urban agriculture into a scalable, climate-resilient, and environmentally friendly food production model. This study underscores the role of integrating IoT and smart control systems into hydroponics as a practical pathway toward sustainable food security in resource-constrained and climate-vulnerable regions.

Keywords: Hydroponics, Agriculture, IoT, Machine Learning

I. INTRODUCTION

Hydroponics is a modern soilless cultivation technique in which plants are grown using nutrient-enriched water solutions that directly supply all the essential minerals required for growth. Unlike conventional soil-based farming, plants in hydroponic systems are supported by inert substrates such as perlite, coco peat, or rock wool, while their roots absorb nutrients directly from the circulating solution. As a core branch of soilless agriculture, hydroponics is particularly effective in controlled environment systems, where parameters such as light, temperature, humidity, pH, and nutrient concentration can be continuously monitored and precisely regulated. This ability to fine-tune growing conditions makes hydroponics not only resource-efficient but also highly suitable for urban agriculture and regions facing land or climate constraints.

The rising global population, rapid urbanization, and climate change have put immense pressure on traditional farming systems, making it increasingly difficult to meet food demands using conventional agricultural practices. Soilless farming techniques such as hydroponics, aeroponics, and aquaponics have emerged as sustainable alternatives, enabling year-round production, higher yields, and significant water savings compared to soil-based farming. IoT combined with Digital Twin technology has the potential to revolutionize agriculture by enabling real-time monitoring, predictive analysis, and efficient resource management. Studies show that this integration can improve crop yield, reduce wastage, and make farming more sustainable [19]. When combined with the Internet of Things (IoT), these systems become even more efficient, as IoT technologies allow real-time monitoring and control of key environmental parameters such as pH, electrical conductivity, temperature, and humidity [18].

Over the past decade, researchers have increasingly investigated the integration of IoT-enabled sensors, artificial intelligence, and cloud-based platforms into hydroponic systems. These innovations not only optimize nutrient management and environmental control but also enhance disease prediction, crop selection, and overall decision-making in controlled environment agriculture. Consequently, a growing body of literature demonstrates diverse approaches—ranging from low-cost monitoring devices and machine learning algorithms to advanced decision support systems—that collectively aim to make hydroponic farming more efficient, scalable, and farmer-friendly.

II. LITERATURE SURVEY

The growing demand for sustainable and efficient farming practices has accelerated research into hydroponics, particularly when combined with emerging technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI). A literature survey serves as the foundation for understanding the progress, challenges, and innovations in this domain. It provides insights into how

researchers across the world are addressing issues of water conservation, nutrient management, disease detection, and automation in controlled agricultural environments. By reviewing past studies, the survey highlights the evolution of hydroponic systems—from basic monitoring setups to advanced, AI-driven predictive models and cloud-integrated platforms. Such an overview not only establishes the context of the present research but also identifies gaps, including cost, scalability, and sensor reliability, that need to be addressed for practical adoption. Ultimately, the literature survey underscores the importance of data-driven, intelligent, and user-friendly hydroponic solutions as a pathway toward sustainable urban farming and global food security.

Jen-Yi Lee et al. [1] introduced an IoT-enabled method to monitor nutrient absorption in hydroponic lettuce cultivation using specialized ion sensors for potassium (K^+), calcium (Ca^{2+}), nitrate (NO_3^-), and sodium (Na^+). Their system not only provided real-time nutrient data but also measured transpiration rates by tracking daily water loss, enabling the correlation between water use and nutrient uptake. The results showed consistent patterns for essential nutrients like potassium and nitrate across summer and winter trials, while sodium showed no such relationship since it is non-essential. This work highlighted how smart sensing can provide farmers with deeper insights into nutrient dynamics, leading to precise fertilizer management, reduced waste, and improved hydroponic efficiency.

Building on this emphasis on real-time monitoring, H. Aditya Pai et al. [2] proposed a cost-effective IoT-based hydroponic setup to enhance cucumber farming in greenhouses. Their system used a master node with two slave nodes for sensor integration and pump control, demonstrating how automation reduces human intervention while increasing crop yield and quality. Compared with traditional farming, hydroponics required less water and produced cleaner crops, though it involved higher costs and technical complexity. The authors also used software simulation to validate faster growth, early flowering, and better spread within 35–40 days. This study complements Lee et al.'s focus on nutrient monitoring by extending smart hydroponic applications to low-cost and scalable greenhouse systems, while also pointing toward research gaps in cost reduction and organic nutrient integration.

In a similar direction of enhancing environmental control, Abhishek Kumar et al. [3] developed a smart IoT-driven hydroponic system combining sensors for water level, pH, temperature, and humidity with cloud storage and real-time mobile app monitoring. A key innovation was the use of PID controllers and crop-specific templates to optimize conditions for different plant types. The system demonstrated impressive efficiency, using only 5% of the water required in conventional farming and enabling indoor cultivation with reduced pest and disease exposure. Unlike

the cucumber-focused system of Aditya Pai et al., this approach highlighted adaptability to urban conditions, stressing the benefits of nutrient control and water conservation for small-scale indoor growers.

Extending this trend of automation, D. Sanjana A. Gharage et al. [4] incorporated Artificial Intelligence into hydroponics by applying Random Forest algorithms to predict plant needs based on sensor inputs for temperature, humidity, pH, light intensity, and water level. This system not only monitored growth conditions but also provided corrective suggestions or automated adjustments, significantly reducing crop failure risks. Tested on spinach and lettuce, the model proved effective in maintaining stable environments and ensuring productivity. Compared to Abhishek Kumar et al.'s rule-based control, Gharage et al. showcased the potential of machine learning for predictive decision-making, suggesting that future hydroponic systems can evolve from simple automation to AI-powered adaptability.

Complementing the AI-driven approach, Siti Nurmaini et al. [5] designed the Hydroponic Farming Ecosystem (HFE), which integrates IoT and cloud computing for both home and commercial users. By incorporating sensors for air and water temperature, pH, EC, light, and water level, the system enabled real-time monitoring through a mobile app while leveraging LoRa communication for long-distance operation. This feature made the system particularly suitable for larger farms or outdoor environments. Tested with pak choy, the system maintained stable growth conditions and improved crop health. Compared to Gharage et al., who emphasized AI-based decision-making, Nurmaini et al. demonstrated the scalability of IoT solutions, showing that communication technology plays a critical role in expanding hydroponics from controlled indoor settings to larger agricultural applications.

Srinidhi H. K et al. [6] extended the integration of IoT and AI in hydroponics by employing machine learning models such as KNN and Lasso Regression to predict nutrient requirements and environmental adjustments. Their system included a compact grow-box setup tested with automated data collection, image-based monitoring using OpenCV, and real-time mobile app visualization. Remarkably, it demonstrated up to 90% water savings compared to traditional farming. While Nurmaini et al. emphasized scalability with long-range IoT, Srinidhi et al. showcased the adaptability of machine learning for small-scale, household-level applications, suggesting that the future of hydroponics lies in combining predictive analytics with user-friendly designs.

Expanding further on the importance of predictive features, Ajay Basil Varghese et al. [7] discussed how IoT-based hydroponic systems, when combined with AI models, can monitor environmental conditions while forecasting

potential crop health issues. Their review introduced examples like iPONICS and systems using Arduino and ESP32, which demonstrated early problem detection and resource efficiency. Compared to Srinidhi et al., who focused on custom machine learning models and grow-boxes, further highlighted commercially relevant systems already in use, emphasizing that real-world applications require not only accurate sensing but also early-warning capabilities to prevent disease or nutrient deficiencies.

Moving from general monitoring to nutrient optimization, Gauri Gadkari et al. [8] developed AI-based models, specifically Random Forest and Support Vector Machines, to determine the optimal nutrient mix in hydroponic systems. Since nutrient management is central to crop performance, their approach demonstrated how machine learning can outperform manual adjustment, making nutrient dosing more precise. This work aligns with Varghese and Deepika's focus on problem prevention but shifts the emphasis toward efficiency in resource use. The transition from crop health monitoring to nutrient optimization reflects how hydroponics research increasingly views AI as essential for both maintaining and enhancing growth conditions.

While Gadkari et al. focused on nutrient balance, Garima Garg et al. [9] introduced CROPCARE, an IoT and machine learning-based system for crop disease detection and prevention. Using MobileNet-V2 trained on over 54,000 images, their system achieved 96.7% accuracy in identifying diseases across 38 crop-disease combinations. Unlike Gadkari et al., who optimized input conditions, Garg et al. Addressed the biological risks of crop failure through mobile image recognition and cloud-based decision support. This complementary perspective underscores that AI in hydroponics can serve two critical roles—enhancing input efficiency and safeguarding against biological threats.

Shifting attention to affordability, Smita Pawar et al. [10] proposed a low-cost IoT-based pH monitoring system, addressing one of the most critical parameters in hydroponics. They emphasized that most commercial systems are expensive due to precision features, whereas their solution focused on reliability and software correction for probe drift. This contrasts with Garg et al.'s high-tech disease detection model by highlighting the practical challenge of accessibility. Pawar et al.'s contribution suggests that democratizing hydroponics requires balancing innovation with affordability to support small-scale farmers.

Similarly addressing practical control, Jumras Pitakphongmetha et al. [11] developed an IoT-based smart greenhouse system to monitor temperature, humidity, water levels, and lighting using NodeMCU as the controller. Their results demonstrated enhanced yield and environmental stability in greenhouse hydroponics. Compared to Pawar et al., who focused on a single parameter (pH), Pitakphongmetha et al. delivered a multi-parameter

integrated system, showing that scaling hydroponics for commercial farming requires holistic monitoring rather than isolated solutions.

Continuing the theme of decision support, Savitri Bevinakoppa et al. [12] designed an IoT-based crop selection system that helps farmers choose the most suitable crops by analyzing environmental data such as soil moisture, temperature, humidity, and pH. Unlike Pitakphongmetha et al., who emphasized greenhouse control, Bevinakoppa et al. shifted the focus to pre-cultivation decision-making. This reflects a broader evolution of IoT in agriculture—from real-time monitoring during growth to strategic planning before planting—thereby reducing crop failure risk at an earlier stage.

Padma Nyoman Crisnapati et al. [13] advanced this trajectory by creating an automated management system for Nutrient Film Technique (NFT) hydroponics using Raspberry Pi and ESP8266 for web-based remote control. Their model allowed users to select crops and automatically configure nutrient and pH settings, representing a step toward context-specific automation. Compared to Bevinakoppa et al.'s crop suitability system, Crisnapati et al. targeted post-selection optimization, suggesting that smart hydroponics can be made adaptive across the entire crop lifecycle.

In a similar vein, Baihaqi Siregar et al. [14] developed a remote monitoring system that tracks hydroponic parameters such as pH, nutrients, and temperature, displaying them on a web platform updated every 10 minutes. This work echoes Crisnapati et al.'s emphasis on remote management but distinguishes itself by focusing on user alerts and actionable notifications, which make it more farmer-centric. Together, these systems highlight that remote accessibility and actionable feedback are key to scaling hydroponic adoption.

Beyond monitoring, Karim Foughali et al. [15] applied IoT and cloud technologies to disease prediction, specifically targeting potato late blight. Their decision support system used Waspote sensor nodes to track humidity and temperature, issuing early alerts to reduce reliance on fungicides. Compared to Garg et al.'s image-based detection, Foughali et al. addressed disease prevention from an environmental-risk perspective, showing that hydroponics and smart farming must integrate both biological and environmental disease models to achieve resilience.

Following this, Gadelhag Mohamed et al. [16] applied Artificial Neural Networks (ANN) to optimize nutrient supply for lettuce across ten treatment conditions, producing five "nutrient recipes." Some ANN-optimized solutions even outperformed standard Hoagland mixtures in plant health indicators. This study ties back to Gadkari et al.'s nutrient optimization work but demonstrates deeper adaptability, as ANN can model nonlinear nutrient-plant relationships more

effectively. The comparative advantage suggests that advanced AI models can refine hydroponics beyond conventional statistical learning.

Broadening the perspective, Pablo Catota-Ocapana et al. [17] reviewed intelligent nutrient control methods in hydroponics, including AI, fuzzy logic, and computer vision approaches. They concluded that integrating these with IoT platforms for real-time monitoring would be essential for scalable adoption. Their synthesis complements Mohamed et al.'s experimental work by emphasizing that the next step is system-level integration of different control models into unified, large-scale solutions.

Finally, R. Monica Dutta et al. [18] contextualized these technological advances within global food security challenges. Reviewing IoT-enabled hydroponics, aeroponics, and aquaponics, they highlighted the potential of soilless agriculture to save 80–90% water while ensuring year-round production. However, they noted that precise environmental control remains a bottleneck, reinforcing the relevance of the sensor, IoT, and AI-driven models presented by earlier researchers. Their review underscores that while individual studies demonstrate promising results, future research must focus on integrating affordability, scalability, and predictive intelligence to transform hydroponics into a globally viable solution.

Finally, Akshay M. J. et al. [19] situated IoT and Digital Twin technologies as a futuristic framework for advancing smart farming. Reviewing applications from soil monitoring to greenhouse management, they emphasized how digital replicas of farm systems, coupled with IoT data streams, can enable real-time monitoring, predictive analytics, and cost-effective decision-making. However, they also acknowledged that widespread adoption depends on overcoming challenges of infrastructure, implementation, and end-user readiness. Their review underscores that while IoT and Digital Twin integration shows strong potential for enhancing productivity and sustainability, future work must address scalability, interoperability, and affordability to make these solutions practical for global agriculture.

The summary of the review being considered are highlighted in the Table 1 as shown.

Reference / Author	Method / Approach	Key Features / Techniques	Findings / Inference
--------------------	-------------------	---------------------------	----------------------

[1]	Developed IoT-based multi-ion monitoring system (IoNSS) using SCISE sensors for nutrient tracking.	Measured NO_3^- , NH_4^+ , K^+ , Ca^{2+} levels; linked to transpiration via VPD; integrated with cloud, MQTT, and real-time analysis.	Enabled precision nutrient management in hydroponics; identified ion-level responses to environmental stress and VPD shifts.
[2]	Developed an IoT-based hydroponic system for cucumber farming using sensor networks.	Used master-slave sensor nodes, simulation models, and low-cost MCUs for real-time monitoring.	Improved crop yield, water efficiency, and growth rate compared to traditional farming.
[3]	Designed a cloud-based IoT system to automate hydroponic farming with real-time monitoring.	Used PID controllers, mobile app integration, and plant profile templates for precision growth.	Achieved faster crop cycles, 95% water savings, and effective nutrient control in small spaces.
[4]	Implemented an AI-integrated hydroponic system with IoT and ML for automated crop growth.	Used ANN, KNN, and Lasso regression with ESP8266 sensors to predict nutrients, detect diseases, and optimize inputs.	Enabled real-time monitoring, early disease detection, and improved yield with minimal manual effort.
[5]	Developed an IoT-based hydroponic farming ecosystem for non-expert users in urban settings.	Used Arduino Uno, MQTT, and multiple sensors (pH, EC, temp, humidity) with mobile app control.	Enabled real-time monitoring, automation, and mobile alerts; effective for small-space farming by beginners.

[6]	Designed an IoT-enabled hydroponic system using ML to monitor and optimize plant growth.	Integrated KNN, Lasso Regression, and OpenCV for nutrient prediction, plant analysis, and image-based growth detection.	Achieved high resource efficiency and improved crop quality; model supports both personal and large-scale farming.
[7]	Reviewed IoT-based plant growth and health monitoring systems for hydroponics.	Surveyed sensors (pH, EC, temp), IoT tools, fuzzy logic, and ML methods for anomaly detection and automation.	Systems improve yield, efficiency, and disease prevention; highlighted scope for AI integration and sustainability.
[8]	Designed an indoor NFT hydroponic system with real-time environmental monitoring for leafy greens.	Used sensors for pH, EC, TDS, DO, temp, humidity, light; Arduino Mega; wireless data logging; stem & height analysis.	Achieved stable growth for Dwarf Pak Choi; system maintained optimal conditions, enabling accurate monitoring and analysis.
[9]	Proposed a smart, sustainable real-time crop disease detection system using mobile vision, IoT, and Google Cloud. Integrated Android app for farmers with multilingual UI.	Used IoT sensors (temp, pH, moisture), MobileNet-V2 with SRCNN for image super-resolution, Firebase for real-time data storage, recommendation system for crops, fertilizers, pesticides, and weather forecasts.	Achieved 96.12% accuracy using PlantVillage dataset; enabled early and accurate detection of diseases in 38 crop classes; empowered farmers with real-time recommendations and government linkage.
[10]	Designed a low-cost pH module for	Used TL072 op-amp for high input impedance	Achieved affordable pH measurement in 5.5–6.5 range

	automation in hydroponic systems; focused on interfacing with microcontrollers like Arduino and Raspberry Pi.	signal amplification; calibrated analog voltage outputs; compensated offsets in software; pH mapped to voltage using BNC-isolated probe.	for hydroponics; emphasized practical calibration, low-cost implementation, and adaptability with different boards.
[11]	Developed a smart hydroponic greenhouse using IoT with remote mobile control via Blynk and real-time monitoring.	Used NodeMCU, DHT11, soil moisture sensor, ultrasonic sensor, and relay modules; data logged on ThingSpeak™; controlled solenoids for irrigation based on water levels and temperature.	Achieved semi-automated greenhouse control with improved plant growth after UV filtering; survival rate increased to 45.83%; demonstrated efficient remote monitoring and control with minimal delay.
[12]	Developed an IoT-based smart system using Raspberry Pi and sensors to predict crop suitability based on environmental data.	Integrated DHT11, soil moisture sensor, pH sensor with Raspberry Pi; used MySQL for crop database; automatic water pump control based on soil moisture; web-based interface built with PHP/HTML.	Successfully identified suitable crops based on real-time sensing of temp, humidity, pH, and moisture; improved yield and reduced manual effort; supported by live web interface and self-controlled irrigation.
[13]	Developed Hommons, a web-based NFT hydroponic management system using IoT and	Arduino Uno with sensors (pH, EC, temperature, ultrasonic), ESP8266 Wi-Fi, Raspberry	Improved monitoring and control efficiency; accurate sensor readings validated against

	automation to reduce manual monitoring efforts.	Pi 2 for webservice; powered by solar energy; responsive UI with Bootstrap, JavaScript, PHP; plant-specific automation settings.	instruments; successful plant growth with reduced human effort; scalable and low-cost for urban farming
[14]	Designed a remote hydroponic monitoring system using microcontroller and wireless communication to track key parameters.	Used Arduino UNO, ESP8266, and ThingSpeak platform; sensors for water level, pH, and temperature; mobile access via IoT dashboard.	Enabled efficient remote monitoring of planting media conditions; real-time alerts and visualization; helped optimize growing environment with low cost and accessibility.
[15]	Developed a Cloud-IoT-based DSS to predict and prevent late blight disease in potatoes using real-time sensor data.	Used wireless sensor nodes (Waspote, Zigbee), Meshlium gateway, and Ubidots cloud platform; applied SIMCAST model to assess disease risk from temp and humidity.	Enabled real-time alerts and treatment decisions; low-cost alternative to traditional weather stations; improved disease management through local data and cloud analytics.
[16]	Used AI techniques (MLP and RBF networks) to optimize nutrient concentrations for soilless agriculture in hydroponics.	Trained models using crop yield datasets; compared prediction accuracy of MLP vs. RBF neural networks; applied in NFT hydroponic	MLP outperformed RBF in prediction accuracy; showed potential for AI-assisted nutrient optimization to boost crop yield and minimize waste.

		setups.	
[17]	Systematically reviewed AI and fuzzy logic-based nutrient control in hydroponic systems.	Analyzed 50 key studies using ANN, CNN, fuzzy logic, ANFIS, and IoT integration for nutrient optimization.	Highlighted improved crop yield, reduced water use (up to 90%), and enhanced automation; emphasized future potential in scalable smart farming.
[18]	Reviewed IoT-based smart precision farming methods in soilless systems like hydroponics, aquaponics, and aeroponics.	Covered CEA, vertical farming, bibliometric trends, smart sensors, AI/ML integration, and environmental controls.	Highlighted soilless systems as scalable solutions for food security; emphasized automation, water efficiency, and future research
[19]	Reviewed integration of IoT with Digital Twin (DT) for futuristic smart farming.	Combined IoT, AI, ML, and Big Data; DT models (data-driven, statistical, physics-based); framework including physical world, DT world, and prediction/analysis world.	Highlighted DT's potential for real-time monitoring, prediction, and decision-making in agriculture; emphasized improved efficiency, cost-effectiveness, reduced waste, and enhanced yield through virtual simulation and optimization.

III. SYSTEM DESIGN

The integration of IoT and automation in hydroponics enables precise monitoring and control of environmental parameters essential for plant growth. The proposed system architecture, as illustrated in Fig. 1, is organized into four main layers: sensing, data transmission, processing and intelligence, and actuation with user interaction.

At the sensing layer, a set of IoT-enabled sensors is deployed to capture real-time data on critical parameters

such as pH, electrical conductivity (EC), temperature, humidity, and water levels. These sensors continuously record variations in the growing environment, forming the foundation for automated decision-making.

The collected data is then transmitted wirelessly through communication protocols such as Wi-Fi, LoRa, or Zigbee to a cloud platform or local edge device. This transmission layer ensures reliable and scalable data flow, making it possible to support both small-scale household systems and large commercial farms.

At the processing and intelligence layer, Artificial Intelligence (AI) and Machine Learning (ML) algorithms analyse the incoming data to identify patterns, detect anomalies, and predict environmental adjustments required for healthy plant growth. For example, predictive models can anticipate nutrient deficiencies, estimate water consumption, and suggest corrective actions before stress affects the crop.

Finally, the actuation and user interaction layer closes the control loop. Automated actuators regulate water flow, nutrient dosing, lighting intensity, and humidity based on AI-driven insights. At the same time, a user-friendly dashboard or mobile application provides farmers with continuous monitoring, real-time feedback, and timely alerts. This interface not only enhances transparency but also allows manual overrides when necessary, ensuring flexibility in operations.

Overall, this system design establishes a closed-loop, intelligent hydroponic ecosystem that minimizes manual intervention, optimizes resource utilization, and supports sustainable crop production.

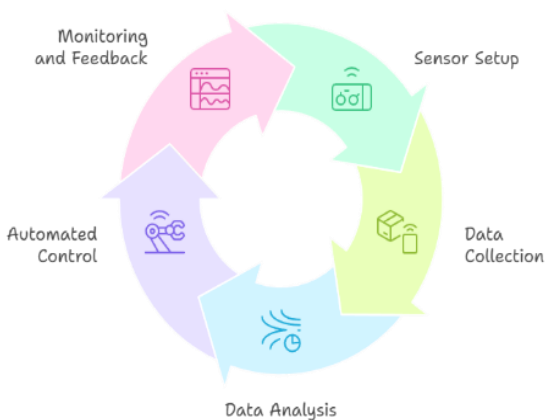


Fig 1. System Design of IoTponics

Building upon the proposed system architecture, the practical implementation can be described in terms of five key stages that ensure seamless monitoring, analysis, and control within the hydroponic environment.

1. Sensor Setup:

The process begins with the installation of IoT-enabled sensors within the hydroponic system. These include pH and EC sensors for nutrient monitoring, temperature and humidity sensors for microclimate assessment, and water level sensors to ensure adequate solution availability. Together, these devices provide the foundational data required for accurate system management, directly supporting the sensing layer outlined in the system architecture.

2. Real-Time Data Collection:

Once deployed, these sensors continuously capture environmental and plant-related parameters. The data is transmitted wirelessly through communication protocols such as Wi-Fi, LoRa, or ZigBee to either a cloud platform or a local edge computing device. This aligns with the transmission layer of the design, ensuring reliable and scalable data flow for both small-scale and large-scale hydroponic setups.

3. Data Analysis:

At the processing layer, AI and Machine Learning algorithms analyse the incoming data to detect anomalies, recognize trends, and predict system requirements. For instance, deviations in pH or EC values can signal nutrient imbalances, while temperature and humidity variations may indicate suboptimal microclimate conditions. Predictive models further enhance system intelligence by forecasting nutrient consumption and water usage, thereby reducing inefficiencies.

4. Automated Control Actions:

Insights generated by the analysis stage are translated into automated responses through actuators. These actuators regulate essential processes such as water circulation, nutrient dosing, lighting control, and humidity regulation. In this way, the actuation layer closes the feedback loop described earlier, ensuring that optimal growth conditions are maintained with minimal manual intervention.

5. Monitoring and Feedback:

Finally, a real-time dashboard or mobile application provides farmers with transparent access to system performance. Sensor readings, control actions, and crop health indicators are displayed in an intuitive interface, while alerts and notifications are issued when abnormal

conditions are detected. This not only supports continuous oversight but also allows for manual adjustments when required, ensuring flexibility and farmer involvement in decision-making.

Together, these stages operationalize the layered system design by establishing a closed-loop control cycle. The seamless integration of sensing, communication, intelligent processing, actuation, and user interaction creates a robust framework for sustainable hydroponic farming, effectively bridging theoretical design with real-world application.

The proposed IoT-based hydroponic system integrates sensors, microcontrollers, data processing, and machine learning to enable intelligent decision-making within a controlled environment. Building upon the previously outlined system architecture, as illustrated in Fig. 2, multiple sensors—including pH, EC, temperature, humidity, and water level—are strategically deployed to continuously capture real-time data on plant growth conditions.

The collected sensor data is transmitted to a central processing unit, where it is filtered, stored, and analyzed to extract meaningful insights. Machine learning algorithms process historical and real-time data to identify growth patterns, predict nutrient deficiencies, and optimize environmental parameters for different crop stages. Based on the analytical outcomes, automated control decisions are generated and executed through actuators such as nutrient pumps, water circulation systems, ventilation units, and LED grow lights. This data-driven automation minimizes human intervention, reduces resource wastage, and ensures consistent crop growth, thereby enhancing productivity and sustainability in hydroponic farming systems.

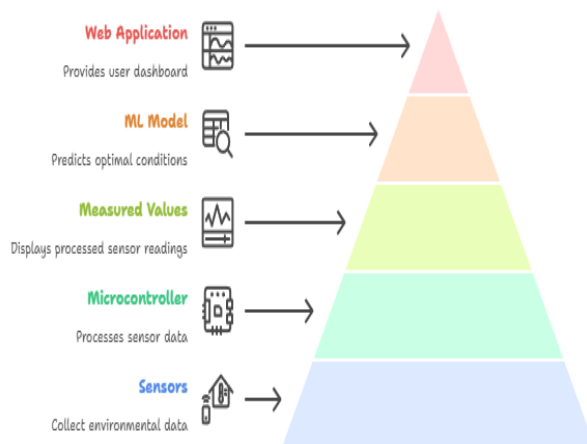


Fig 2. Methodology of IoTponics

1. Sensor Data Collection

The system begins with sensors that monitor the hydroponic environment. A pH sensor checks whether the nutrient solution is acidic or alkaline, since plants thrive only within a specific pH range. An EC (Electrical Conductivity) sensor is used to measure the concentration of nutrients dissolved in the water, ensuring that plants receive the right amount of food. A temperature sensor continuously monitors the environmental temperature to maintain plant-friendly conditions, while a humidity sensor tracks the moisture content in the surrounding air, which directly impacts transpiration and growth. Together, these sensors create a detailed picture of the growing environment.

2. Microcontroller Integration

All the collected sensor readings are transmitted to a microcontroller such as Arduino, ESP32, or Raspberry Pi. The microcontroller acts as the central hub, gathering data in real-time from each sensor. Its primary role is to coordinate communication, ensure smooth data acquisition, and provide a reliable link between the physical sensors and the processing layer.

3. Data Processing

Once the sensor data reaches the microcontroller, it undergoes basic processing. The raw measurements are cleaned, organized, and formatted into a structured dataset, typically arranged as [pH, EC, Temperature, Humidity]. This transformation makes the data suitable for further computational analysis and ensures consistency across multiple readings.

4. Machine Learning Model Input

The processed data is then forwarded to a Machine Learning (ML) model. This model has been trained on historical sensor readings and plant growth patterns. It analyses the input values and provides intelligent insights. For example, it can predict the plant's health condition, determine whether irrigation is required, or suggest nutrient adjustments. By doing so, the system moves beyond simple monitoring and becomes predictive and adaptive.

5. Web Application Output

Finally, the predictions and recommendations from the ML model are displayed on a web application dashboard. This dashboard provides farmers, researchers, or growers with a user-friendly interface showing real-time sensor values, system status, and actionable suggestions. The application allows remote monitoring and decision-making, making hydroponics management more efficient, data-driven, and accessible.

IV. RESULTS AND DISCUSSION

The analysis of the reviewed studies indicates that integrating IoT-enabled sensing, AI-driven analytics, and automated control systems into hydroponic farming has a transformative impact on production efficiency, crop health, and resource management. AI-based models such as ANN, Random Forest algorithms, and fuzzy logic controllers further enhanced system performance by predicting nutrient requirements, optimizing fertigation schedules, and detecting plant diseases at an early stage, while computer vision tools added a complementary layer of crop health assessment. Cloud-connected platforms improved accessibility and scalability by allowing real-time remote monitoring and control, thereby reducing the need for constant manual supervision. Collectively, these findings confirm that IoT- and AI-driven hydroponic systems substantially advance precision, sustainability, and productivity, aligning with the progress documented across the reviewed literature [1]–[18], while also underscoring the need for future research to improve affordability, reliability, and energy efficiency for broader implementation.

The reviewed studies consistently demonstrate that the integration of IoT-enabled sensing, automation, and AI-driven analytics in hydroponics has significantly advanced precision farming. Results across multiple experiments highlight water savings ranging from 80–95% compared to soil-based cultivation, with real-time monitoring of parameters such as pH, electrical conductivity (EC), and nutrient concentration ensuring optimized plant growth and reduced fertilizer wastage [1]–[3].

Advanced ion-specific sensors were shown to track nutrients like nitrate, potassium, and calcium with high precision, linking nutrient uptake to transpiration patterns, which improved fertilizer management and revealed plant responses to environmental stress [1]. IoT-driven cucumber farming systems achieved faster growth and improved yields compared to traditional cultivation, though challenges in cost and scalability persisted [2].

Automation through controllers and cloud integration has further enhanced efficiency. Cloud-based hydroponic systems with PID controllers and crop-specific templates achieved faster crop cycles and up to 95% water savings, supporting small-space and urban agriculture [3]. Studies integrating AI techniques confirmed the potential of machine learning models such as Random Forest, ANN, KNN, and Lasso Regression to optimize nutrient supply, predict plant health issues, and minimize wastage.

Vision-based mobile systems achieved over 96% accuracy in crop disease identification across 38 classes [9], while IoT-cloud decision support systems were used for potato disease prediction, reducing dependency on chemical fungicides [15]. Both approaches highlight the complementary role of AI and IoT in safeguarding crop

health, whether through visual recognition or environmental risk modelling.

Affordability and accessibility were also addressed. Low-cost pH monitoring systems designed for Arduino-compatible modules ensured affordability without compromising accuracy [10].

Similarly, web-based and remote IoT dashboards allowed real-time monitoring even in small-scale or resource-constrained setups [13], [14]. Overall, the literature confirms that IoT- and AI-enabled hydroponics can stabilize growth conditions, reduce water and nutrient usage, and increase crop productivity. Future research must therefore focus on scalability, low-maintenance sensors, and cost-effective automation, while leveraging predictive intelligence for nutrient management and disease prevention [17].

Fig. 3 compares the performance of different machine learning models used in hydroponic applications. The results show that artificial neural networks deliver the best predictive accuracy, while models such as SVM, KNN, and random forests provide competitive but slightly lower outcomes. Simpler approaches like lasso regression and fuzzy logic are less effective, yet remain useful for specific monitoring and control tasks. This suggests that advanced learning methods are better suited to capture the complex dynamics between plant growth and environmental conditions.

Furthermore, the superior performance of neural network-based models highlights their ability to learn nonlinear relationships and interactions among multiple environmental parameters, such as nutrient concentration, temperature, humidity, and light intensity. However, the increased computational complexity and training requirements of these models necessitate adequate processing resources and well-curated datasets. In contrast, traditional models like SVM and KNN offer faster implementation and easier interpretability, making them suitable for small-scale or resource-constrained hydroponic setups. Therefore, selecting an appropriate machine learning model involves balancing prediction accuracy, system complexity, and practical deployment constraints.

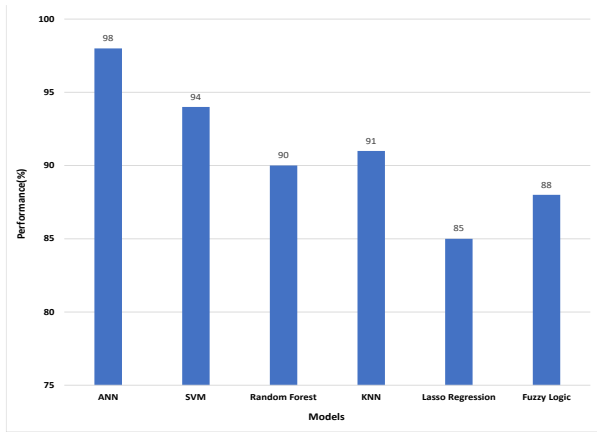


Fig. 3: Performance landscape of machine learning models in hydroponics: highlighting accuracy trends across reported studies.

Fig. 4 highlights the types of sensors and equipment most frequently adopted in hydroponic research. pH and EC sensors are the most common, reflecting their importance in managing nutrient balance. Temperature and humidity sensors also appear regularly, emphasizing the need for environmental regulation. Microcontrollers such as Arduino and NodeMCU, along with actuators like pumps and solenoids, are widely used to enable automation and reduce manual intervention in controlled farming systems.

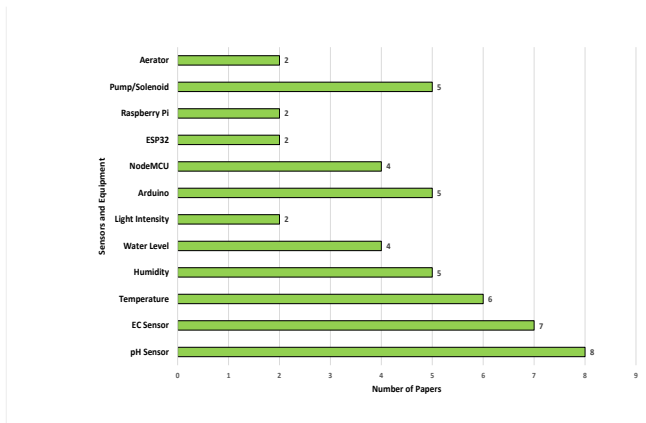


Fig.4: Sensor and equipment hotspots in hydroponics research: mapping the most frequently adopted technologies.

V. RESEARCH CHALLENGES

Hydroponics, as a controlled environment and soilless farming technique, provides a sustainable pathway for urban food production but faces several technical and operational challenges that limit its scalability. Key issues include sensor drift and frequent calibration requirements, noisy and inconsistent data streams, the interdependent regulation of pH, EC, temperature, and humidity, as well as biofouling

and water hygiene problems that compromise system stability. Recent trends point toward IoT-enabled monitoring, edge–cloud hybrid architectures, AI- and machine learning–driven predictive analysis, and advanced control strategies such as PID and model predictive control, along with emerging tools like computer vision and digital twins for crop health assessment. Addressing these challenges requires the development of robust, low-maintenance sensors with built-in drift compensation, as well as preprocessing and anomaly detection methods to ensure reliable data for machine learning predictions.

Similarly, optimized PID controllers with anti-windup and delay compensation can improve precision in nutrient and pH regulation, while sustainable practices such as closed-loop nutrient recycling, UV-based water sanitation, and energy-efficient scheduling of lighting and HVAC systems can reduce operational costs and environmental impact. Furthermore, the integration of interoperable IoT frameworks with secure communication protocols, explainable dashboards for user-friendly monitoring, and human-centered automation can enhance scalability, reliability, and farmer adoption. Together, these advancements can mitigate current limitations and establish hydroponics as a smarter, more efficient, and sustainable farming solution for the future.

The experimental setup of the IoTponics system integrates multiple IoT sensors, actuators, and microcontroller units to form an automated hydroponic environment.

1. Hardware Components Used

The major hardware components include:

1. Microcontroller based sensors to (Arduino/ESP32): Responsible for interfacing all sensors, collecting real-time data, and controlling actuators such as the water pump.
2. pH Sensor: Measures the acidity/alkalinity of the nutrient solution to ensure optimal nutrient absorption.
3. DHT11/DHT22 Temperature–Humidity Sensor: Monitors environmental air temperature and humidity.
4. Moistur sensors: Detects the moisture content within the grow medium, determining the water requirement for plants.
5. Turbidity Sensor: Monitors the transparency of water to detect impurities in the nutrient solution.
6. LDR (Light-Dependent Resistor): Measures the ambient light intensity affecting plant photosynthesis.

7. Water-Circulation Pump Motor:Used to circulate nutrient solution throughout the system, ensuring uniform distribution.
8. Green LED Grow Lights:Provide artificial illumination to support plant growth in indoor/low-light environments.
9. Relay Module:Enables microcontroller-based control of the water pump.
10. LCD Display (16×2):Shows real-time parameters such as pH, turbidity, temperature, and humidity.

2. Software Components Used

1. FlaskWeb Framework:Powers the web application for real-time monitoring and user interaction.
2. Python (Backend):Handles database operations, ML predictions, and API endpoints.
3. SQLite Database:Stores historical sensor logs and pump status.
4. HTML, CSS, Bootstrap:Used to design the dashboard, log pages, and user interface.
5. Joblib (Machine Learning Model Loader): Loads the Random Forest model and preprocessing components.
6. Arduino IDE:Used for writing and uploading firmware scripts for sensors and pump control.
7. Matplotlib / Excel:Used to generate graphs for performance analysis.

collect environmental data, while the pump motor circulates the nutrient water.

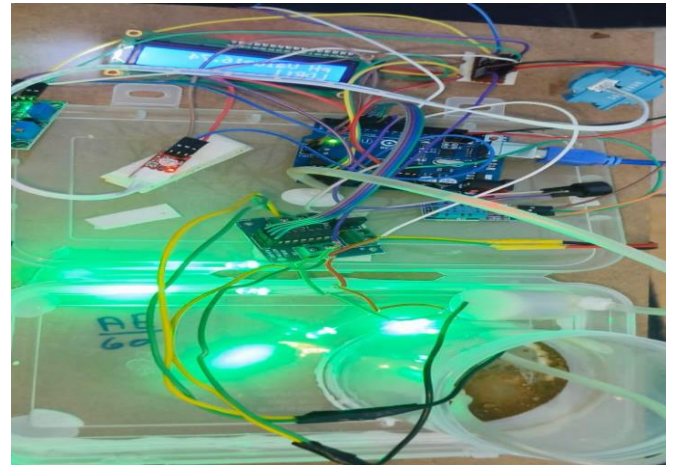


Fig 5. Green-light hardware setup

Analysis:

The presence of green grow lights ensures supplemental illumination, while the wiring layout ensures stable data collection. The pump tubes demonstrate efficient water circulation.

Dashboard Interface

The web dashboard displays real-time values of the major parameters including pH, humidity, temperature, moisture, LDR, and predicted pump status.As illustrated in Fig. 4.3, the dashboard presents a user-friendly interface summarizing system status, monitored features, and live sensor data.



Fig 4.Hydroponic System

depicts the assembled hydroponic system used for nutrient circulation and plant growth monitoring.

3.Hardware Prototype Setup

The hardware prototype consists of interconnected modules including sensors, pump motor, grow lights, and microcontroller.Fig. 4.2 shows the green-light hardware setup consisting of sensors, wiring connections, and the microcontroller used in the hydroponic system.Sensors

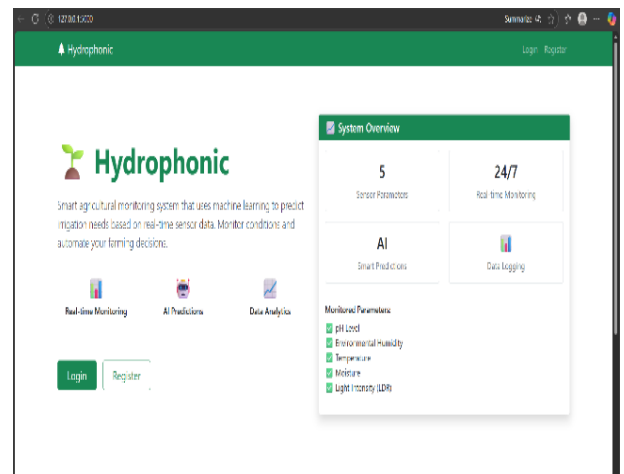


Fig 6. Dashboard

Analysis:

The dashboard supports data visualization and is responsive. Sensor values are color-coded to enhance readability and enable faster decision-making by the user.

Live Data API Output

The live data system fetches sensor readings every few seconds and performs ML-based pump prediction. As depicted in Fig. 4.4, the live-data interface provides continuously updated environmental parameters along with the system’s pump status.

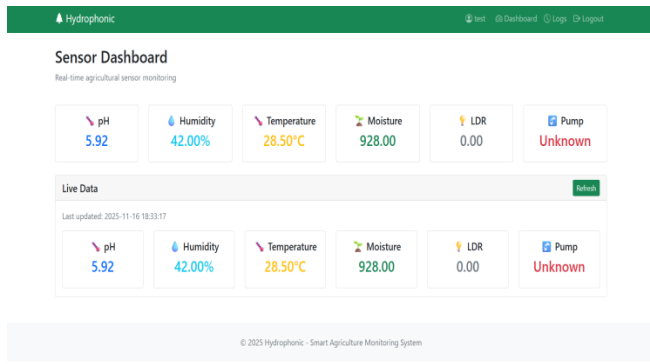


Fig 7. Live-data section

Analysis:

The API provides stable, low-latency updates, and the prediction model validates pump decisions before forwarding commands to Arduino.

Historical Sensor Logs

Historical sensor data plays a crucial role in understanding environmental patterns, identifying system anomalies, and enabling long-term decision-making in hydroponic farming. In this project, all real-time sensor readings—such as pH, humidity, temperature, moisture, light intensity (LDR), and the ML-predicted pump status—are automatically stored in the local SQLite database. Every entry is saved along with a precise timestamp, ensuring accurate chronological tracing of the system’s behaviour.

This database-driven approach enables the system to maintain a detailed record of environmental conditions over time, making it possible to perform trend analysis, generate graphs, and evaluate how various parameters affect plant growth. The Sensor Logs page provides a clean and intuitive interface where users can view the most recent entries or apply date-based filtering to inspect logs from a specific

day. This makes monitoring both real-time and historical trends simple and accessible for users.

Fig.5. demonstrates the log history section, enabling analysis of previously captured sensor data for performance monitoring. To improve readability, the logs are displayed in a tabular format with alternating row highlights, clearly structured columns, and labeled parameters.

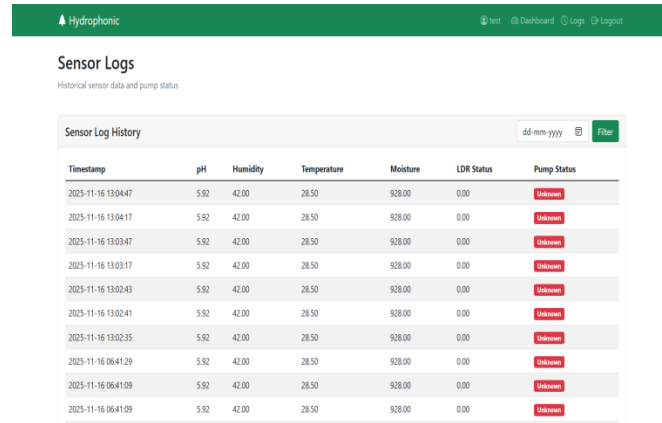


Fig 8. Log Page

Analysis:

The logs show consistent sensor readings, confirming the reliability of serial communication and database insertion logic.

Performance Analysis (with Graphs & Explanations)

Below are the graphical analyses of the key environmental parameters measured during the hydroponic system operation. These graphs help understand the stability, behavior, and reliability of each sensor over time.

pH Level Over Time

The pH graph shows minor oscillations between 5.86 and 5.95, which is normal and expected in hydroponic nutrient solutions. The ideal pH range for most hydroponic plants is 5.5 to 6.5, and the values measured fall consistently within this range. The smooth curve indicates that the pH sensor readings are stable and accurate, with no sudden spikes or drops. This stability confirms that the nutrient solution is well-balanced and that the sensor integration with Arduino and the Flask backend is functioning correctly. As depicted in Fig. 4.6, the pH readings fluctuate within a narrow range, indicating stable but dynamic changes in the hydroponic environment. The smooth curve indicates that the pH sensor readings are stable and accurate, with no sudden spikes or drops.

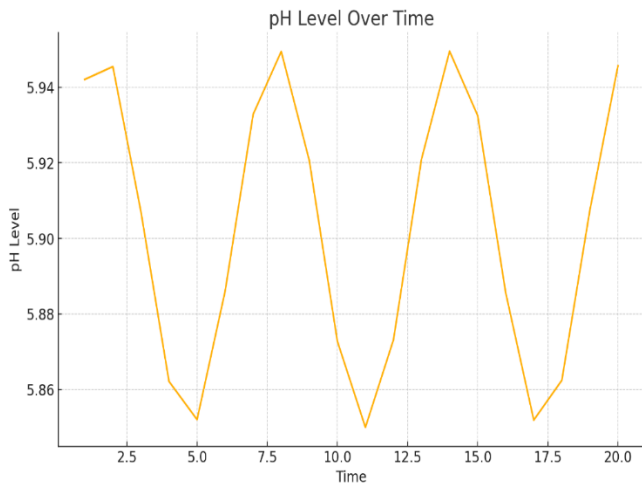


Fig 9. pH level graph

Humidity Variation Over Time

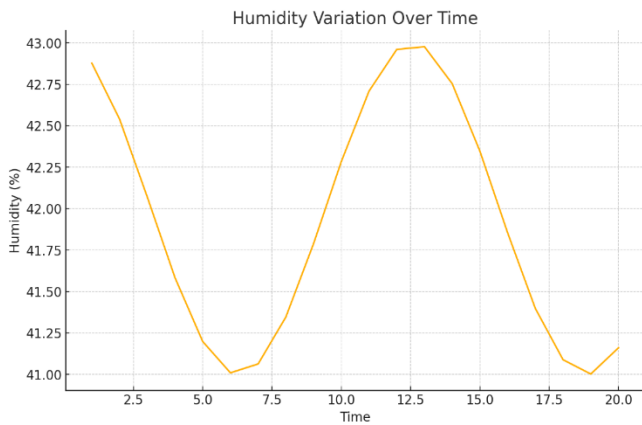


Fig 10. Humidity Level

Humidity levels fluctuate slightly between 41% and 43%, which remains within the typical indoor hydroponic range. The data reflects normal room humidity variations caused by environmental conditions. The graph pattern shows a sinusoidal movement, indicating consistent measurement accuracy from the DHT11 sensor. Since humidity affects transpiration and nutrient uptake, maintaining a steady range helps ensure optimal plant growth. Fig. 4.7 presents the humidity variation over time, reflecting the dynamic but controlled atmospheric conditions of the hydroponic setup.

Temperature Trend Over Time

The temperature graph shows values between 27.4°C and 28.6°C, which are suitable for warm-season hydroponic plants. Fig. 4.8 shows the variation in temperature levels over time, indicating a gradual rise followed by a steady decline within the monitored period. The slow fluctuations

demonstrate good thermal stability in the growing environment. The DHT sensor captures temperature changes accurately, and the system's readings indicate no overheating, no external interference, and stable operating conditions. The consistency here also supports the ML model because temperature is one of the key input features for prediction.

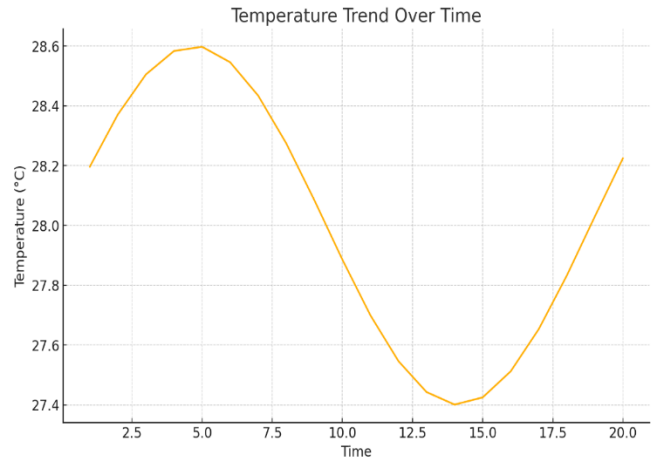


Fig 11. Temperature Level Graph

Moisture Level Over Time

The moisture levels range between 905 and 935, reflecting the moisture sensor's numeric scale. Fig. 4.9 shows the fluctuation in moisture levels over time, illustrating a gradual decline followed by a steady rise during the observation period.

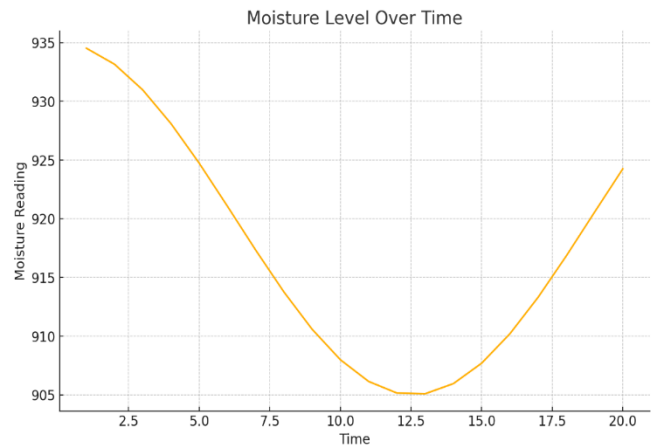


Fig 4.9: Moisture Level

This downward-upward curve represents real behaviour as water evaporates or gets absorbed, followed by system adjustment. When moisture levels drop toward the lower

boundary, the ML model predicts Pump ON, ensuring water circulation. This graph validates that the water regulation mechanism works correctly, and the moisture values provide reliable input to the machine learning model.

VI. CONCLUSION

Integrating Internet of Things (IoT), Artificial Intelligence (AI), and smart control systems into soilless agriculture is revolutionizing the way crops are cultivated, monitored, and managed. IoT-enabled hydroponic systems have consistently demonstrated significant improvements in resource efficiency, achieving water savings of up to 80–90% compared to conventional soil-based farming while maintaining or even enhancing crop yields. Real-time monitoring of critical environmental parameters such as pH, electrical conductivity, temperature, and humidity enables precise adjustments that reduce human intervention, minimize nutrient imbalances, and lower the risk of crop stress. At the same time, AI-driven models provide predictive insights for nutrient management, irrigation scheduling, and early disease detection, further enhancing productivity and sustainability. However, challenges such as high initial setup costs, sensor calibration and maintenance requirements, and the energy demands of controlled environments continue to limit widespread adoption. Despite these constraints, the integration of IoT and AI in hydroponics holds immense potential to address pressing global food security challenges, particularly in urban and resource-constrained regions. By enabling data-driven, precise, and sustainable cultivation practices, these technologies pave the way toward scalable, climate-resilient, and high-yield food production systems that align with the future of smart agriculture.

REFERENCES

- [1] Y.-M. Wu, S.-Y. Liu, B.-Y. Shi, J.-Y. Peng, Z.-W. Kao, H.-Y. Chung, C.-Y. Lin, W. Fang, and L.-C. Chen, "Field study correlating nutrient absorption and transpiration in lettuce hydroponics using an IoT-interfaced solid-state ion sensor array," *IEEE Sensors Lett.*, vol. 8, no. 6, pp. 1–4, Jun. 2024, doi: 10.1109/LESENS.2024.3402325.
- [2] H. A. Pai, et al., "Observing environmental conditions in IoT-based hydroponics farming for better cucumber cultivation," *Int. J. Smart Agricult.*, vol. 11, no. 2, pp. 112–123, 2022.
- [3] A. Kumar, et al., "Monitoring and accelerating plant growth using IoT and hydroponics," in *Proc. Int. Conf. Smart Agricult. Technol.*, 2022, pp. 45–52.
- [4] S. A. Gharage, et al., "AI based smart hydroponics system," *Int. J. Innov. Res. Technol.*, vol. 8, no. 5, pp. 233–240, 2022.
- [5] S. Nurmaini, et al., "Applied Internet of Things for smart hydroponic farming ecosystem (HFE)," *Indones. J. Electr. Eng. Informat.*, vol. 10, no. 3, pp. 550–561, 2022.
- [6] H. K. Srimidhi, H. S. Shreenidhi, and G. S. Vishnu, "Smart hydroponics system integrating IoT and machine learning algorithm," in *Proc. Int. Conf. Recent Trends Electron., Inf., Commun. Technol.*, 2020, pp. 261–264.
- [7] A. B. Varghese and D. M. P. Deepika, "Enhancing hydroponic production: A review of plant growth and health monitoring system," *Int. J. Comput. Appl.*, vol. 183, no. 2, pp. 34–41, 2022.
- [8] G. Gadkari, S. Shirke, R. Somani, A. Kulkarni, and P. Mulay, "Optimising nutrient formulations through artificial intelligence for hydroponic cultivation," *J. Emerg. Agricult. Technol.*, vol. 9, no. 1, pp. 25–36, 2022.
- [9] G. Garg, et al., "CROPCARE: An intelligent real-time sustainable IoT system for crop disease detection using mobile vision," in *Proc. IEEE Int. Conf. IoT Smart Agricult.*, 2023, pp. 12–19.
- [10] S. Pawar, S. Tembe, and S. Khan, "Design of an affordable pH module for IoT-based pH level control in hydroponics applications," *Int. J. Electron. IoT Appl.*, vol. 7, no. 4, pp. 200–208, 2023.
- [11] J. Pitakphongmetha, et al., "Internet of Things for planting in smart farm hydroponics style," in *Proc. Int. Conf. Comput. Commun. Syst.*, 2023, pp. 44–49.
- [12] S. Bevinakoppa, et al., "IoT based smart prediction system for crop suitability," *Int. J. Smart Agricult. Syst.*, vol. 15, no. 3, pp. 178–186, 2023.
- [13] P. N. Crisnapati, et al., "Hommons: Hydroponic management and monitoring system for an IoT-based NFT farm using web technology," *Int. J. Web Appl. Agricult.*, vol. 6, no. 2, pp. 50–58, 2023.
- [14] B. Siregar, et al., "Remote monitoring system for hydroponic planting media," in *Proc. Int. Conf. Green Technol. Smart Agricult.*, 2023, pp. 77–85.
- [15] K. Foughali, et al., "Using cloud IoT for disease prevention in precision agriculture," *Int. J. Precis. Agricult. IoT Syst.*, vol. 4, no. 1, pp. 88–99, 2023.
- [16] G. Mohamed, et al., "Optimising nutrient formulations through artificial intelligence model to reduce excessive fertigation in lettuce grown in hydroponic systems," *IEEE Access*, vol. 11, pp. 1–12, 2023, doi: 10.1109/ACCESS.2023.3571730.
- [17] P. Catota-Ocapana, et al., "Smart control models used for nutrient management in hydroponic crops: A systematic review," *Comput. Electron. Agricult.*, vol. 214, pp. 108–121, 2023.
- [18] M. Dutta, et al., "Internet of Things-based smart precision farming in soilless agriculture: Opportunities and challenges for global food security," *IEEE Access*, vol. 13, pp. 34242–34259, 2025.
- [19] M. J. Akshay, B. G. Premasudha, and S. B. Hegde, "IoT to digital twin: A futuristic smart farming," in *Proc. Int. Conf. Smart Syst. Appl. Electr. Sci. (ICSSAES)*, 2024, pp. 1–7, doi: 10.1109/ICSSAES62373.2024.10561335.