International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 17s, 2025
https://theaspd.com/index.php

Enhancing Hydroponics Efficiency Using Iot-Based Automated Monitoring And Sustainable Crop Production System

Dr Prashant Nitnaware[1], Monicka Nitin Jagtap[2]
[1]Professor, Information Technology Department, Pillai College of Engineering, New Panvel, India, pnitnaware@mes.ac.in
[2]Lecturer,Computer Technology Department, Bharati Vidyapeeth Institute of Technology, Navi Mumbai, India, monickajagtap@gmail.com

Abstract
The increasing demand for sustainable agricultural practices, coupled with the challenges of limited arable land and water resources, has driven the need for more efficient and innovative farming systems. One of the main challenges in enhancing hydroponics efficiency with IoT-based systems is the high initial cost of setting up advanced sensor networks and automation technologies. The objective of this study is to develop and evaluate an IoT-based automated monitoring system to optimize hydroponics efficiency, enhance crop yield, and reduce resource waste. Environmental and nutrient parameters such as pH, temperature, humidity, and light intensity were continuously collected using sensor networks. Pre-processing, including data cleaning and Gray-Level Co-occurrence Matrix (GLCM) analysis, enabled accurate detection of subtle environmental changes impacting crop health. Growth optimization was achieved using a hybrid Poplar Optimization Algorithm–Smart Flower Optimization Algorithm (POA-SFOA), allowing precise control over water, nutrients, and light inputs. The Multiplex Adaptive Modality Fusion Graph Attention Network (MAMFGAT) was applied to analyze sensor data interdependencies, enabling smart, adaptive decision-making. This system supports sustainable agriculture by maximizing yield, minimizing resource use, and automating operations for long-term efficiency. The result shows that the proposed system increases crop yield by about 25-30% as compared to 10-15% for the semi-automated and baseline yield for the traditional methods, implemented using Python software. Future work can explore integrating AI-driven predictive analytics for early stress detection and yield forecasting in hydroponic systems.
Keywords: *Sustainable Agricultural, Internet of Things, Hydroponics, Crop Production, Gray-Level Co-Occurrence Matrix, Optimization Algorithm.*

INTRODUCTION

As the global population continues to grow, the demand for food increases, and so does the pressure on traditional farming methods. In the look of climate variation, dwindling arable land, and water scarcity, innovative agricultural techniques such as hydroponics have emerged as viable alternatives. However, despite its benefits, hydroponics requires precise monitoring and control of environmental variables such as pH, temperature, humidity, light, and nutrient concentration [1]. This is where the IoT enters the scene. This fusion of technology and agriculture is revolutionizing food production by enabling real-time data collection, predictive analytics, and intelligent automation [2-3]. Understanding Hydroponics and Its Challenges bypasses traditional soil-based cultivation by providing plant roots with direct access to nutrient solutions. Despite these advantages, hydroponic farming faces several operational challenges as Precision Control for maintaining the right balance of nutrients, pH levels, and water temperature is critical [4]. Labour-intensive monitoring is constant monitoring to confirm optimal plant health. System Failures are manual systems that are prone to human error and inefficiency. In hydroponic systems, IoT devices can monitor environmental and system variables with high precision and send real-time data to a central platform or mobile application [5]. Key components of an IoT-based hydroponic system include Sensors to measure pH, electrical conductivity (EC), temperature and light intensity, CO_2 levels, and water levels. Microcontrollers are devices like Arduino or Raspberry Pi that process sensor data and control system operations [6].
Actuators are operating pumps, fans, lights, and nutrient dispensers based on sensor input. Connectivity Modules are Wi-Fi, Bluetooth, or Lora modules that connect the system to the cloud. Cloud Platform is to stores data, analyses trends, and enables remote access and automation. User Interfaces are mobile apps or dashboards that display data in real-time and allow user interactions [7-9]. With IoT-based automation, hydroponic systems gain several efficiency advantages such as real-time Monitoring farmers can monitor key metrics remotely and receive instant alerts if any value falls outside the ideal range. With automated Control of sensor inputs, the system can automatically adjust nutrient delivery, pH, lighting schedules, and temperature control systems without manual intervention. Data-Driven Decision Making is by analysing historical data, farmers can optimize growing conditions, predict plant health issues, and improve yield forecasting [10-12]. Sustainability is unique to the core goals of integrating IoT with hydroponics. Here's how this fusion promotes environmentally friendly farming water conservation hydroponics already uses up to 90 percentages less liquid than traditional farming. IoT enhances this

by preventing leaks, optimizing recirculation, and minimizing evaporation [13]. Reduced Chemical Use is precise nutrient delivery ensures minimal waste and avoids over-fertilization, dropping the danger of water pollution [14]. Renewable Integration network systems can be powered using solar panels and linked with smart grids to further reduce environmental impact [15]. A temperature sensor detects that the ambient temperature has risen above 28°C. The small controller activates a cooling fan. The pH sensor indicates that the good food solution is becoming too acidic. The grower receives a mobile alert that the water reservoir is 20% full, prompting a refill before plants are stressed. Connectivity Issues is reliable internet is needed for cloud-based systems [17-19]. The integration of Artificial Intelligence (AI) and machine learning (ML) with IoT in hydroponics is the next frontier. AI algorithms can predict optimal harvesting times, identify diseases via image recognition, and automate complex decision-making processes. Blockchain could also be introduced to enhance transparency in the food supply chain [20]. Government support, smart agriculture policies, and growing consumer demand for clean, local produce are likely to accelerate the adoption of these technologies. The continuing sections are organized as follows: The literature review was described in Section 2, the proposed technique was described in Section 3, the results were discussed in Section 4, and the paper's conclusion was described in Section

LITERATURE SURVEY

Agriculture has always been at the heart of human civilization, but with the rising global population, urbanization, and climate change, the demand for more efficient, sustainable, and scalable methods of food production has never been greater. Joshitha et al., [21] utilized the synergy between microcontrollers and sensors, this hydroponic system, once automated, provides constant monitoring and precise control of environmental factors, minimizing drastically the requirement for human intervention. By employing the use of automation and sensors, the system optimizes the utilization of resources, reduces environmental footprint, and allows people to cultivate crops with minimal experience. Hanafi et al., [22] concluded paper further discusses the role of data analytics and AI in helping better decision-making processes in hydroponic environments The study stresses the importance of innovation to resist world food sustainability and security, which makes hydroponics an urgent solution to agriculture in the future. Rofiansyah et al., [23] performed the test results to demonstrate that the Hydro Farm system has a high degree of accuracy level of 96% in recording plant health conditions, with sensors providing accurate and precise data for effectively controlling hydroponic parameters. The outcome shows that there is potential to mirror this model in expanding diet safety and supportable agriculture among high-density populations. Dutta et al., [24] examined the large-scale deployment of ML in smart hydroponics in the manuscript too. The manuscript discusses the introduction of the 'Smart Hydro Kit,' a novel, portable device used for monitoring and automating the environmental parameters for hydroponic onion growth to enhance sustainability. Findings indicate that onion yields by the application of hydroponics are strongly greater than those by the use of soil. The findings are also confirmed through simulation with the 'Aqua Crop' model. Catota et al., [25] examined the outcomes there are great leaps forward but also highlighted key hurdles that exist, among which are the requirement for precision sensors, coping with huge data quantities, and capability to allow models to make it feasible in terms of differing crops and weather. The findings of this review provide a solid ground for the evaluation of the success of the control models and their application in real agricultural conditions. Aurasopon et al., [26] integrate wireless sensor nodes that relay data to a central control unit for real-time watching and regulation. The research emphasizes the vast potential of smart hydroponic systems in revolutionizing legacy farming practices and providing much-needed support to small farmers. Varghese et al., [27] suggested ML algorithm and data analysis methodology evaluation for detecting anomalies, predictive maintenance, and optimization of growth conditions. This research paper also argues the possibility of such systems to revolutionize controlled environment agriculture and set future research directions in sensor development, data processing, and integration into AI. Khadijah et al., [28] suggested an IoT-based system proposes an attempt to introduce farmers to an integrated and ease-to-use platform for monitoring and controlling important parameters essential for plant growth and delivering maximum productivity and output in hydroponic farming. The findings of this research provide useful contributions to the capability of IoT technologies in transforming precision agriculture and sustainable food production. Naresh et al., [29] proposed that the COVID-19 pandemic has brought to light the interconnected dangers in centralized, concentrated agriculture. Decentralized precision strategies can provide stability. Hydroponics and vertical farm revolutions can enable viable intensification to address nutritional needs in the future. Rajaseger et al., [30] determined recent trends in Hydroponics, emphasizing new developments in smart farming technology, including Demotics, Data Achievement, Remote Agriculture, and autonomous AI systems. The review also describes various forms and benefits of smart farming technology, with a focus placed on the achievement of efficiency in this new area. The review also discusses future objectives and potential developments, providing avenues for innovations in hydroponic smooth agri-business.

RESEARCH PROPOSED METHODOLOGY

Enhancing hydroponics efficiency using an IoT-based automated monitoring and sustainable crop production system involves integrating IoT sensors to monitor key environmental parameters such as temperature, humidity, pH levels, nutrient concentration, and water flow in real-time. The system will collect continuous data, which will be analyzed using advanced analytics and ML algorithms to optimize growing conditions and automate irrigation, nutrient delivery, and climate control. Additionally, the system will employ predictive models to anticipate crop needs and adjust variables automatically, ensuring optimal growth conditions and resource efficiency. The methodology also focuses on incorporating renewable energy sources, such as solar power, to reduce environmental impact and enhance the sustainability of the hydroponic system. This method aims to improve crop yield, reduce water and nutrient waste, and enable scalable, sustainable urban farming solutions.

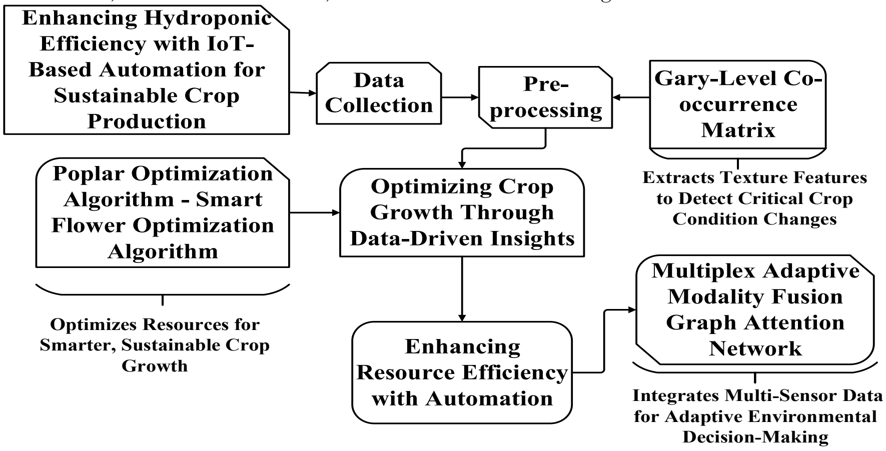

Figure 1: Block Diagram of the Proposed Work

Figure 1 shows enhancing hydroponic efficiency through IoT-based automation to promote sustainable crop production. Environmental data is collected and pre-processed using methods like the GLCM, which extracts texture features to detect subtle yet critical changes in crop conditions. For optimized growth, a hybrid approach combining the POA and SFOA is employed to fine-tune environmental parameters and resource allocation, ensuring smart, sustainable crop management. The MAMFGAT integrates data from various sensors such as temperature, humidity, pH, and light intensity capturing interdependencies across modalities to enable intelligent, adaptive decision-making in real-time. Together, these technologies create a robust, efficient, and data-driven hydroponic system that maximizes yield and resource use.

(a) Data Collection

Data was collected continuously throughout the crop growth cycle using an integrated IoT system equipped with various sensors. Key environmental and nutrient parameters such as pH level, electrical conductivity, temperature, humidity, water level, and light intensity were monitored in real-time. The system transmitted data to a cloud-based IoT platform for storage, visualization, and analysis. Additional observational data, including plant height, leaf count, and growth rate, were recorded manually at regular intervals to evaluate crop development. This combination of automated and manual data collection enabled a comprehensive assessment of system performance, crop health, and resource efficiency.

Table 1: IoT-Based Hydroponics: Environmental and Growth Parameter Analysis

Parameter	Unit	Day 1	Day 7	Day 14	Day 21	Day 28
pH Level	pH units	6.2	6.3	6.4	6.5	6.6
Electrical Conductivity (EC)	mS/cm	1.2	1.3	1.4	1.5	1.6
Temperature	°C	22	23	24	25	26
Humidity	%	65	60	58	55	53
Water Level	cm	30	28	26	24	22
Light Intensity	Lux	1500	1600	1700	1800	1900
Plant Height	cm	5	12	18	24	30
Leaf Count	Count	2	4	6	8	10
Growth Rate	cm/day	0.5	1.0	1.2	1.5	1.7

Table 1 presents key environmental and growth parameters monitored throughout the crop growth cycle in an IoT-based hydroponics system. The data includes pH levels, electrical conductivity, temperature, humidity, water level, light intensity, plant height, leaf count, and growth rate, measured over 28 days. Initially, the pH level and electrical conductivity gradually increased, indicating optimal nutrient availability and stability for plant growth. Temperature showed a steady rise, reflecting the controlled environment, while humidity decreased over time, suggesting a natural reduction in moisture levels as plants matured. Water levels consistently decreased, demonstrating the system's efficient water usage. Light intensity was progressively increased, optimizing photosynthesis conditions for the plants. The plant height, leaf count, and growth rate data show a clear upward trend, indicating healthy crop development, with the growth rate reaching 1.7 cm/day by Day 28. This comprehensive dataset provides valuable insights into crop health, resource usage, and the efficiency of the IoT-based monitoring system in maintaining optimal conditions for sustainable hydroponic farming.

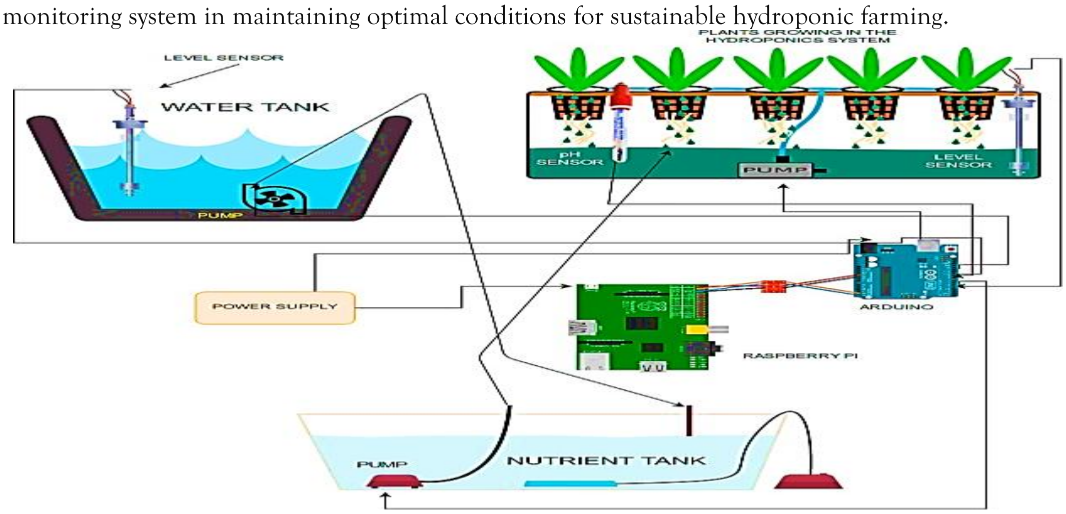

Figure 2: IoT-Based Automated Monitoring and Control System for Hydroponics

Figure 2 shows the workings of an automatic hydroponics system consisting of IoT devices responsible for its control and monitoring. Water is supplied via pumps from water and nutrient tanks to nurture plant development in the hydroponics system. Among hydroponic systems, sensors such as a pH sensor and level sensors help to constantly monitor the environmental condition. The readings from the different sensors are fed to a Raspberry Pi microcontroller, which acts as the CPU. Where extra interfacing is required, an Arduino" board may be used for such sensors. According to the sensor data and predefined parameters, Raspberry Pi will control the pumps for the watering and feeding cycle to ensure the plants grow well. The water level in the water tank is monitored via a level sensor. The system is fully powered, ensuring computerized and remote management of the hydroponic growth environment.

(b) Pre-processing

Furthermore, once the data had been collected, the following step was to set up data pre-processing to ensure that the accuracy and dependability of the dataset were maintained for further analysis. It included cleaning the data by removing all noise and inconsistencies, as well as standardization with a common format. Techniques like the GLCM were employed for feature extraction through texture pattern analysis of the environmental data to detect subtle changes in growth conditions. Such changes that are sometimes unnoticeable could pose a great threat to crop health. With GLCM's feature extraction techniques, there must have been concrete texture-based features from the images and sensor data that greatly contributed to identifying critical changes in important parameters like temperature, humidity, and nutrient levels affecting plant growth directly.

(i) Gary-Level Co-occurrence Matrix (GLCM)

Based on the intended views for GLCM concerning bettering and sustaining crop production, understand the application of GLCM for image-based monitoring, particularly in terms of plant health analysis. GLCM is largely used in image processing as the main descriptor of leaf texture analysis to detect diseases or stresses in plants automatically in a hydroponics system enabled by IoT. GLCM-based equations/features for facilitating hydroponic crop monitoring through image processing.

Workable solutions call for collaborative action on the part of government, educational institutions, private industry, and farmers. Investments in research and development, subsidies for smart farming tech, and farmer training programs will help democratize access to these advanced systems. Open-source hardware and software platforms also play a key role in the democratization and customization of IoT-based hydroponics for a wide variety of users. Contrast dealings with the local dissimilarities in the GLCM.

$$Contrast = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} (i-j)^2 p(i,j) \quad (1)$$

Where $p(i,j)$ Probability of pixel pair in the GLCM

Interpretation in hydroponics is high contrast might indicate leaf spots or diseases causing rough textures. Correlation reflects how correlated a pixel is to its neighbour over the entire image.

$$Correlation = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \frac{((i-j)^2)}{\sigma_i \sigma_j} p(i,j) \quad (2)$$

Where $\sigma_i \sigma_j$ Mean and standard deviation of GLCM rows/columns. Interpretation helps in detecting consistent growth patterns; irregularities may signal stress. Energy (Angular Second Moment) measures the uniformity of the texture.

$$Energy = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} p(i-j)^2 \quad (3)$$

High energy is a uniform texture and low energy is a varied texture. In hydroponics: Healthy leaves often show consistent patterns; a sudden drop in energy might suggest nutrient deficiency.

Homogeneity processes the closeness of the circulation of rudiments in the GLCM to its diagonal.

$$Homogenity = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \frac{p(i-j)^2}{1+|i-j|} \quad (4)$$

Higher value is smoother texture and the hydroponics is a change in homogeneity might indicate early signs of disease or physical damage.

Application in IoT-based Hydroponics cameras monitor crops, analyse leaf texture using GLCM, and send data to a cloud system. Based on the GLCM features automated alerts can be sent if plant stress is detected. Nutrient delivery or lighting can be adjusted automatically. Overall crop health is continuously evaluated with minimal human effort.

Hydroponics, a scheme of growing plants lacking soil by utilizing mineral nutrient results in a water solvent, represents a significant shift from conventional farming. This soilless farming technique allows plants to grow in controlled environments with minimal water, space, and resource use, offering high yields and reduced environmental impact. By enabling crops to be cultivated indoors, in greenhouses, or even in urban vertical farms, hydroponics provides a pathway to localized food production and year-round harvesting.

However, hydroponic systems require detailed control over conservational parameters such as pH, temperature, humidity, nutrient concentration, and light. Manual monitoring and adjustments are not only labour-intensive but also susceptible to human error, which can lead to suboptimal growth conditions or even crop failure. This is where IoT technology comes into play, revolutionizing the way hydroponic systems are managed and optimized.

Table 2: Gary-Level Co-occurrence Matrix

Algorithm 1: Gary-Level Co-occurrence Matrix
System Setup: Install IoT sensors and cameras for monitoring plant health and environmental conditions. ***Image Capture:*** Continuously take images of plant leaves for texture analysis. GLCM Extraction: Analyze images to extract features like contrast, correlation, energy, and homogeneity. ***Data Transmission:*** Send environmental and GLCM data to a cloud platform for analysis. ***Plant Health Analysis:*** Evaluate plant stress, diseases, or nutrient deficiencies based on GLCM features. ***Adjustments:*** Modify temperature, light, humidity, and nutrients based on health analysis. ***Continuous Monitoring:*** Track plant health in real-time using IoT sensors. ***Automated Alerts:*** Notify users of any deviations in plant health or environmental conditions. ***Automated Response:*** Trigger system corrections automatically based on detected issues. ***Optimization:*** Continuously optimize the system for efficient, sustainable crop growth.

The IoT-based hydroponic system starts with sensor and camera installation to observe the health of plants as well as the disorder of the environment. Continuous images of plant leaves are taken for texture analysis to include features like contrast, correlation, energy, and homogeneity, which are extracted using GLCM techniques. This data, together with environmental parameters, will be sent to the cloud for analysis. The system will evaluate the health of plants through given GLCM features to identify plant stress, diseases, or nutrient deficiencies. In the event of detected problems, the system has the competence to automatically adjust the levels of temperature, light, humidity, and nutrients to create the best conditions for plant growth. Continuous real-time monitoring ensures that plant health is followed and alerts are sent to the user in the event of a deviation. Then it will trigger an action to correct the problem and continue with smooth operation. Continuous feedback optimizes the system for sustainable and efficient crop production to achieve maximum yield but with minimum resource usage.

(c) Optimizing Crop Growth Through Data-Driven Insights

The collected data can be further analyzed by hydroponics systems along with IoT sensors to optimize crop development by correlating the environments with the performance of plants. Advanced data analysis tools assess their measures toward temperature, humidity, and light intensity in bringing changes to important growth attributes, including plant height, number of leaves, and overall health. Along with the optimization methods, techniques like POA-SFOA may be enlisted. This hybrid will harness the strengths of both optimisation techniques to finetune environmental parameters along with resource allocations for better and more accurate control over features such as water use, light exposure, and so on. By integrating POA-SFOA, the system can make smarter, data-driven adjustments in real-time, ensuring crops receive optimal conditions throughout their growth cycle. Through continuous feedback and adaptation, growers can maximize yield, accelerate growth rates, and improve overall crop quality, leading to more efficient and sustainable agricultural practices.

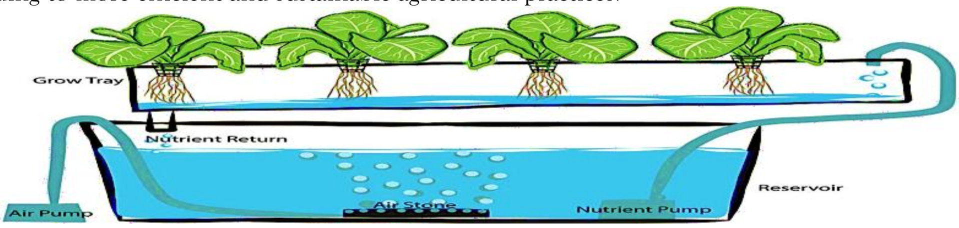

Figure 3: Hydroponic System with Automated Nutrient Delivery and Aeration

A recirculating hydroponic system is a means of rising plants in a medium-less environment, and this is illustrated in Figure 3. The plants are maintained on top of a Grow Tray held above a Reservoir containing a solution of nutrients and water. Here, nutrient-rich water is obtained from the reservoir by the Nutrient Pump and pumped to the grow tray where it provides the plants with essential elements to the roots suspended in water. After that, the nutrient solution is drained back into the reservoir through Nutrient Return, allowing for maximum recycling. An Air Pump, linked to an Air Stone, injects fine bubbles of air into the nutrient solution in the reservoir, which proves to be vital for healthy root growth. The setup represents a simple yet effective hydroponic system that could be further automated through IoT-based monitoring for precise control of nutrient levels, pH, temperature, and aeration for maximizing plant growth and efficient use of the resources.

(i) Poplar Optimization Algorithm - Smart Flower Optimization Algorithm (POA-SFOA)

The integration of the Poplar Optimization Algorithm with the SFOA into hydroponic systems aims to enhance efficiency through IoT-based automated monitoring and sustainable crop production. While specific equations for POA-SFOA in hydroponics are not readily available, this study can infer the following general equations based on the principles of these algorithms and their application in hydroponic systems. The possibilities for this technological advancement are limitless, not confined to commercial agricultural production but also to households, educational institutions, and research centers. Smart hydroponics kits are now available to home customers, allowing them to grow their favourite culinary herbs or vegetables from their kitchen or balcony. Simultaneously, huge vertical farms in urban centers utilize the IoT for space and output optimization while minimizing ecological footprints. Hydroponics with IoT functionalities is a possible food security answer in areas where water is scarce or the soil conditions are poor. Even if it has advantages, the IoT hydroponic systems nevertheless face certain challenges. The initial installation cost can be high due to the sensors and controller hardware and networking infrastructure. There is also a learning curve in understanding the technology, data interpretation, and maintenance of the systems. Cybersecurity is another issue; any system connected to the Internet can potentially be hacked, causing an interruption in the functioning of the system. Besides, low connectivity in rural or remote areas may also limit real-time operations for cloud-based systems. Objective Function for Nutrient Optimization is hydroponic systems, optimizing nutrient delivery is crucial for plant growth. An objective function can be formulated to minimize nutrient waste and maximize plant health.

$$\text{Min } f(x) = \sum_{i=1}^{n}((nutri_{i,input-}nutri_{i,output})^2) + \gamma(ph_i - ph_{opt})) \quad (5)$$

Where $f(x)$ represents the decision variables (e.g., nutrient concentrations).The $(nutri_{i,input-}nutri_{i,output)})^2$ are the input and output concentrations of the i nutrient and γ is a regularization parameter. $(ph_i - ph_{opt})$ are the measured and optimal pH levels for the i nutrient solution. This equation aims to minimize the difference between input and output nutrient levels while maintaining optimal pH conditions, thereby enhancing nutrient efficiency.

The Environmental Control Objective is conserving optimal ecofriendly conditions is vital for plant health. An objective function can be designed to regulate factors like temperature, humidity, and light intensity.

$$Mini\ g(y) = \sum_{j=1}^{m}(temp_j - temp_{opt})^2 + (humi_i - humi_{opt})^2 + (light_i - light_j)^2 \quad (6)$$

Where $g(y)$ represents the environmental control variables.$temp_j$ and $humi_i$ and the $light_i$ are the measured temperature, humidity, and light intensity at the j sensor.$temp_{opt}$ and $humi_{opt}$, $light_j$ are the optimal values for these parameters. This function seeks to minimize the deviations of environmental parameters from their optimal values, ensuring conditions favourable to plant growth. Efficient energy use is critical in automated hydroponic systems. An objective function can be established to minimize energy consumption while maintaining system performance

$$Mini\ h(z) = \sum_{k=1}^{p}(power_{k,consume}.time_k + \beta \sum_{k=1}^{p} deviation) \quad (7)$$

Where $h(z)$ represents the energy-related variables. $power_{k,consume}$ is the power consumed by the k component.$time_k$ is the operational time of the component. $\sum_{k=1}^{p} deviation$ is the deviation component's performance from its optimal state.β is a weighting factor. This equation aims to minimize the total energy consumption of the system while accounting for performance deviations, promoting energy efficiency.

These equations could thus be worked into IoT-based hydroponic systems whereby nutrient delivery, environmental setting, and energy application can be optimized thereby improving overall system efficiency and sustainability. IoT implies a network of interconnected physical devices that are added with sensors, software, and connectivity competencies to capture and exchange data. Placing IoT in hydroponic systems allows these devices to automatically monitor the critical environmental parameters and adjust the variables of the system so that optimal growth conditions can be maintained. Such automation greatly enhances crop production, minimizes manpower, and optimizes resources, thus rendering hydroponic farming highly efficient, scalable, and sustainable.

An IoT-based automated monitoring system in hydroponics essentially consists of various types of sensors (for temperature, humidity, pH, electrical conductivity, etc.), microcontrollers, plus suitable actuators such as water pumps, fans, and lights. Basically, these combinations of tools will gather information and send it to a central controller or cloud-based platform and then respond to user-definable thresholds. For instance, the pumping system may be triggered to add nutrient solution if the nutrient level falls below the selected threshold; in scenarios where the temperature is above the optimum reading, the fans or cooling system could be activated to bring back balance.

Table 3: POA-SFOA

Algorithm 2: POA-SFOA
Initialize IoT System: Set up sensors, actuators, and a cloud platform. **Data Collection:** Continuously gather environmental and nutrient data. **Data Transmission:** Send data to a cloud platform for real-time analysis. **Monitor Plant Growth:** Track plant health indicators (height, leaf count). **Analyze Nutrient Levels:** Ensure optimal nutrient and pH levels. **Environmental Control:** Adjust temperature, humidity, and light. **Nutrient Adjustment:** Modify nutrient delivery based on analysis. **Energy Monitoring:** Optimize energy use for system components. **Real-time Response:** Automatically adjust components when needed. **Continuous Optimization:** Use algorithms to improve system efficiency.

Table 3 displays the IoT-based Automated Monitoring for Hydroponic System Efficiency Enhancement includes setting up the IoT system (which contains sensors and actuators) and cloud platforms for smooth data collection and analysis. Environmental parameters and nutrient data are gathered continually to monitor other critical factors such as temperature, humidity, light intensity, and pH level. This data is analyzed in real-time in the cloud platform to monitor plant health parameters such as height and leaf count. From the above data analysis, nutrient levels and pH are determined and analyzed to maintain their optimum levels for plant growth. Not only does the system manage other environmental conditions, but it also does so by altering temperature, humidity, and light levels. Nutrient delivery is modified on demand to use resources more efficiently. Energy consumption is monitored closely, then optimized rendering to the needs of each component, resulting in reduced costs. When there are deviations from the optimal conditions, it responds in real-time, automatically adjusting the related components. Dynamic optimization is also continuing through advanced algorithms, thus further improving the efficiency of the system, sustaining growth, and achieving sustainability.

(d) Enhancing Resource Efficiency with Automation

In hydroponic systems that are automated by IoT technology, waste is reduced while the efficiency of inputs-water, nutrients, or energy- is enhanced. The automated systems use present information from sensors to ensure usage of resources only when and where required. Adapted scheduling of irrigation, nutrient delivery, or lighting is just one way that sensor information is used. To make this possible, MAMFGAT methods can also be utilized. MAMFGAT is a joint deep-learning methodology that allows data from multiple sensor modalities like temperature, humidity, pH, and light intensity to be captured from the environment and worked on concerning interdependencies among different sensor modalities. By using graph attention mechanisms, MAMFGAT girds the scheme with the capacity to attend and adapt the system to any environmental changes for smarter, more intelligent, and more efficient decision-making. Such meticulous control also lessens overconsumption, consequently shrinking operational costs plus its environmental impacts. Oftentimes, engineered systems can be managed around the clock, whereby conditions remain optimal without constant human intervention, thus adding to efficiency and sustainability. With such automation in routine tasks, the grower can actively engage in more strategic aspects of crop production and ensure resources are used in efficient and sustainable ways.

(i) Multiplex Adaptive Modality Fusion Graph Attention Network (MAMFGAT)

The MAMFGAT technique is an advanced model designed to enhance predictions in complex systems by integrating multiple data modalities through graph attention mechanisms. In the background of hydroponics efficiency, MAMFGAT can be applied to optimize IoT-based automated monitoring and sustainable crop production systems. Graph Attention Mechanism Employs Graph Attention Networks (GATs) to process data structured as graphs, where nodes represent entities (e.g., sensors, environmental factors) and edges denote relationships or interactions between them. The attention mechanism assigns different importance to neighbouring nodes, permitting the model to attention to more relevant information.

$$Attention(h_i, h_j) = softmax\left(\frac{\exp\left(leakyReLu(a^T[Wh_i||Wh_j])\right)}{\sum_{k \in N} exp(leakyReLu(a^T[Wh_i||Wh_k]))}\right) \quad (8)$$

Here, h_i, h_j are feature vectors of nodes, Wh_i is a weight matrix, a^T is a learnable attention vector, and Wh_k denotes the neighbours of node i.

Multiplex Adaptive Modality Fusion integrates multiple data modalities (e.g., temperature, humidity, pH levels) by adaptively fusing them. This fusion agrees on the method to leverage complementary information from different sources, improving prediction accuracy.

$$h_{fused} = \sum_{m-1}^{m} \alpha_m . modality_{\ m} \quad (9)$$

In this equation, h_{fused} represents the fused feature vector is the adaptive weight for modality mmm, and $modality_{\ m}$ is the feature vector from the modality. The weights α_m are learned during training to emphasize more informative modalities. Prediction Layer after feature aggregation and fusion, MAMFGAT utilizes a prediction layer to output the desired results, such as crop yield or nutrient requirements. This layer typically involves a Multi-Layer Perceptron (MLP) that processes the fused features to make final predictions.

$$y^{\wedge} = \sigma(w_{out}.ReLu(w_{fused}.h_{fused} + b_{fused}) + b_{out}) \quad (10)$$

Here, $y^{\wedge}$ is the predicted output, w_{out} , w_{fused} are bias terms, and σ denotes an activation function (e.g., sigmoid or softmax). By applying MAMFGAT, IoT-based hydroponic systems can achieve more accurate monitoring and control, leading to optimized resource usage and sustainable crop production.

In addition to improving operational efficiency, the combination of IoT enhances data-driven decision-making. The continuous stream of data collected can be analysed to identify patterns, forecast plant growth trends, and even predict potential system failures before they occur. This predictive capability is particularly valuable for commercial hydroponic farms where downtime or inefficiencies directly impact profitability. Moreover, by storing data in the cloud, farmers can access and manage their hydroponic systems remotely using smartphones or computers, adding another layer of convenience and control.

Sustainability is another crucial pillar in this evolving landscape. Traditional agriculture consumes approximately 70% of the world's freshwater and contributes significantly to greenhouse gas emissions. Hydroponic farming, especially when enhanced with IoT-based automation, addresses many of these challenges. Studies have revealed that hydroponic classifications can use up to 90 percentages less water compared to soil-based agriculture, as water is recirculated and not lost to runoff or evaporation. Additionally, since hydroponics is typically conducted in controlled environments, the essential for chemical pesticides and herbicides is drastically reduced, leading to cleaner and safer produce.

EXPERIMENTATION AND RESULT DISCUSSION

The experimentation for enhancing hydroponics efficiency using an IoT-based automated monitoring and sustainable crop production system involved setting up a controlled hydroponic environment integrated with IoT sensors to track vital parameters such as nutrient levels, pH, temperature, humidity, and light intensity. The system's performance was assessed by comparing crop growth rates, resource consumption, and overall yield in automated and manual monitoring conditions. Results indicated that the IoT-based system significantly improved crop yield and growth efficiency by upholding optimal environmental conditions through real-time monitoring and automated adjustments. Moreover, the system demonstrated a reduction in water and nutrient waste, highlighting its sustainability benefits. The integration of ML models also enhanced prediction accuracy for future crop needs, contributing to better resource management. Overall, the results confirmed that IoT-enabled automation leads to more efficient and sustainable hydroponic crop production, offering a scalable solution for urban farming systems.

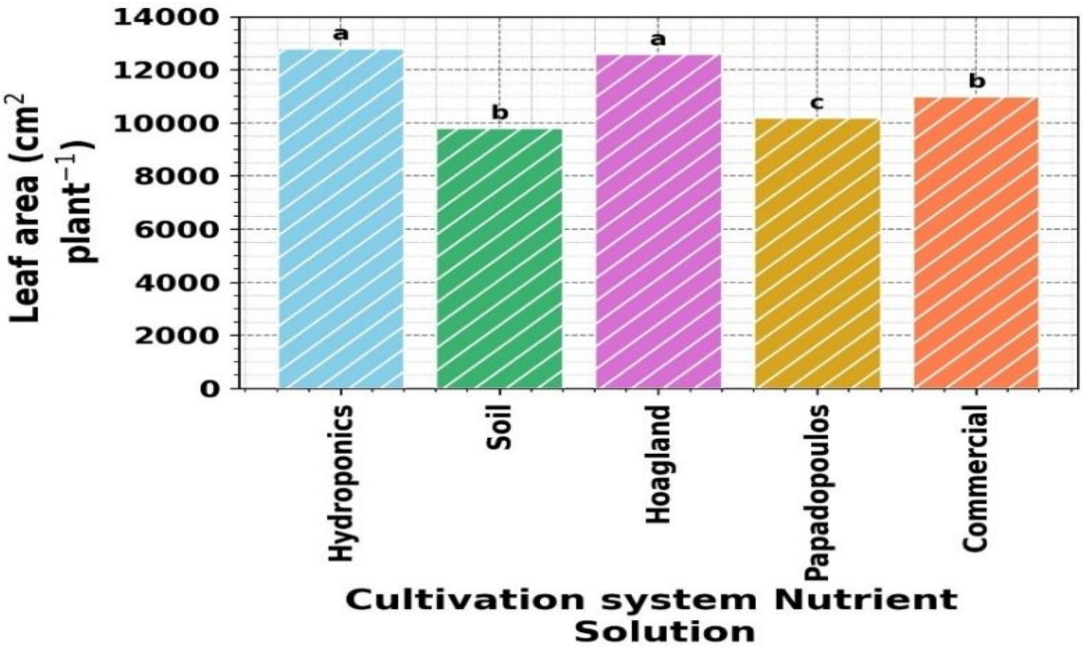

Figure 4: Comparison of Leaf Area in Different Cultivation Systems with Various Nutrient Solutions

Figure 4 presents the plant leaf area evaluated in several cultivation systems and nutrient solutions. A maximum leaf area of 12,100 cm² was found in hydroponics, and this was the highest among all systems. This might be due to controlled nutrient delivery and optimum conditions for growing in the system. Comparatively, leaf area in soil was lower at 9,900 cm². This may be produced by limitations in the availability of nutrients and variations in soil conditions. In different nutrient solutions, Hoagland's solution resulted in a leaf area of 12,010 cm², comparable to that obtained with the hydroponic system, indicating the important role played by proper balance of nutrients. Papadopoulos' solution produced a leaf area of 10,000 cm², while commercial nutrient solutions gave a leaf area of 11,000 cm². These findings suggest that although the development medium is important, it is the nutrient solution that affects plant growth most, hydroculture, and the right nutrient giving the highest leaf areas.

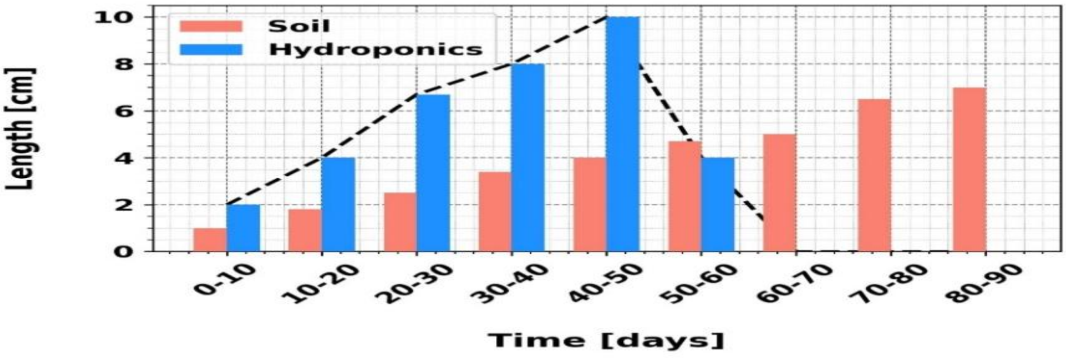

Figure 5: Comparison of Plant Growth in Soil vs Hydroponics Over Time

Figure 5 presents the plants monitoring up to their growth provided an opportunity to compare the growth performance with soil and hydroponic systems. For the first ten days, plant length was mostly comparable in both systems: soil-grown plants attained 1 cm by day 10, while hydroponic plants only grew to 2 cm. By days 40 through 50, major observable differences showed up with soil-grown plants attaining a length of 4 cm while hydroponic plants went as much as 10 cm. The striking contrast in plant growth highlights the full growth potential of hydroponic systems likely due to their controlled nutrient supply, water availability, and environmental conditions. The hydroponic system opted to further growth by positively customizing these parameters. Hydroponic systems are therefore able to provide better plant development in their late phase than soil methods when managed properly.

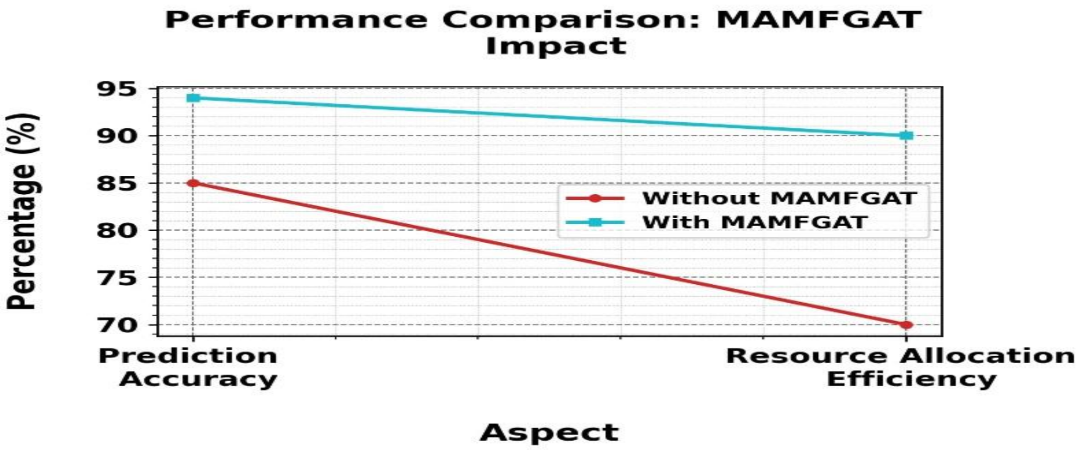

Figure 6: Impact of MAMFGAT on Hydroponic System Performance

Figure 6 displays the Merger Adaptive Modality Fusion Graph Attention Network has significantly improved the working of hydroponics systems. It touches the prediction accuracy and resource allocation efficiency. The system achieved a prediction accuracy of 85% without MAMFGAT. With MAMFGAT, however, accuracy rose to 94%. The benefit was MAMFGAT's efficient and effective analysis and integration of data from multiple sensor modalities, improving the system's prediction capabilities, which resulted in improved forecasting of crop growth and environmental conditions. Meanwhile, resource allocation efficiency increased from 70% to 90% with MAMFGAT adopted. MAMFGAT uses advanced deep learning techniques to provide more effective optimization of irrigation, nutrient delivery, and energy consumption for better efficiency and wastage prevention. The benefits of such improvements highlight the importance of adopting advanced ML techniques in the enhancement of hydroponic farming systems.

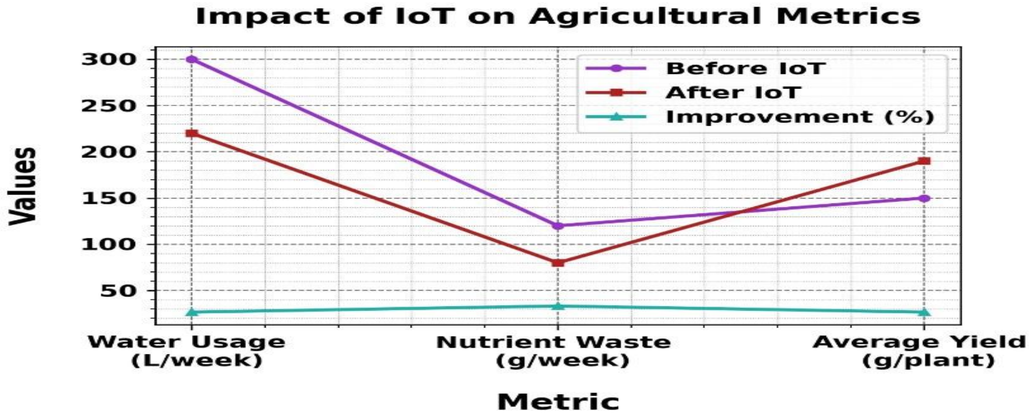

Figure 7: Impact of IoT Integration on Hydroponic System Efficiency

Figure 7 illustrates Innovations brought about through IoT-based monitoring in hydroponic systems have brought about great efficiency in the usage of resources as well as high crop yield. Water consumption was 300 L/week before the implementation of IoT, which was reduced to 220 L/week after the integration of IoT driving a reduction of 26.7%. This reduction projection in water consumption mirrors the effectiveness of real-time monitoring in either optimizing irrigation scheduling or avoiding wastage. Similarly, nutrient wastage reduced from 120 g/week to 80 g/week giving a reduction of 33.3% in waste. This reduction is solely due to the very precise delivery of nutrients enabled by the IoT sensors which have been monitoring and correcting the nutrient supply to meet the needs of plants. The average yield in plants also increased in yield by 26.7% from 150 g/plant to 190 g/plant showing how great an effect augmentation has in environmental management. This could well be summarized by the future potential of IoT to bring improvements in resource efficiency and enhance the production of hydroponic farming systems.

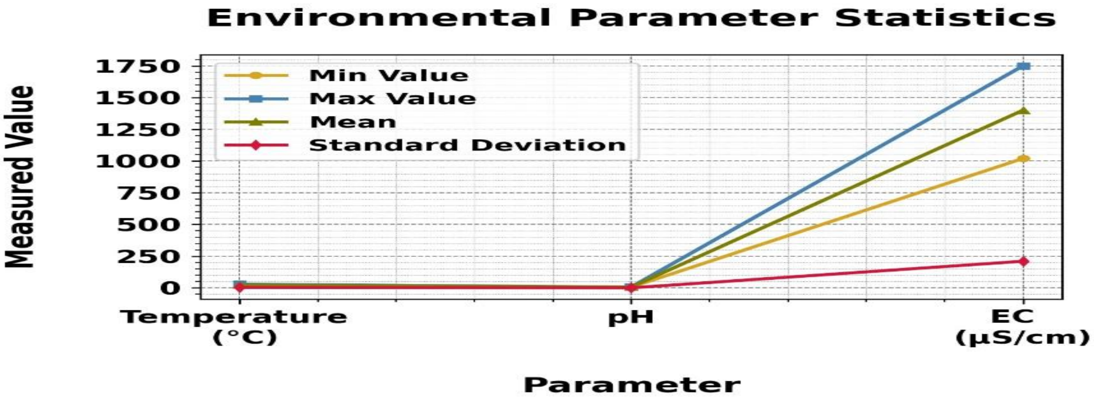

Figure 8: Environmental Parameters for Optimizing Hydroponic Systems

Figure 8 displays the investigation focused on monitoring various environmental parameters that govern hydroponic crop growth; temperature varied from 18.2°C to 29.7°C and averaged 23.4°C with a standard deviation of 3.2°C, which is vital for metabolic activities and nutrient uptake. The pH was maintained between 5.6 and 6.9, with a mean of 6.3 and a standard deviation of 0.4; this range was important for nutrient obtainability and plant health. Proper maintenance of pH ensures that essential nutrients remain soluble and available to the plants. Additionally, electrical conductivity (EC) was recorded to vary from 1020 µS/cm to 1750 µS/cm with an average of 1400 µS/cm and a standard deviation of 210 µS/cm, which is an indicative parameter of overall nutrient concentration in the system. These parameters were constantly monitored by IoT sensors, ensuring real-time data collection allowing for precise control to keep plant growth at an optimum, enhance resource-use efficiency, and increase yield in the hydroponic system.

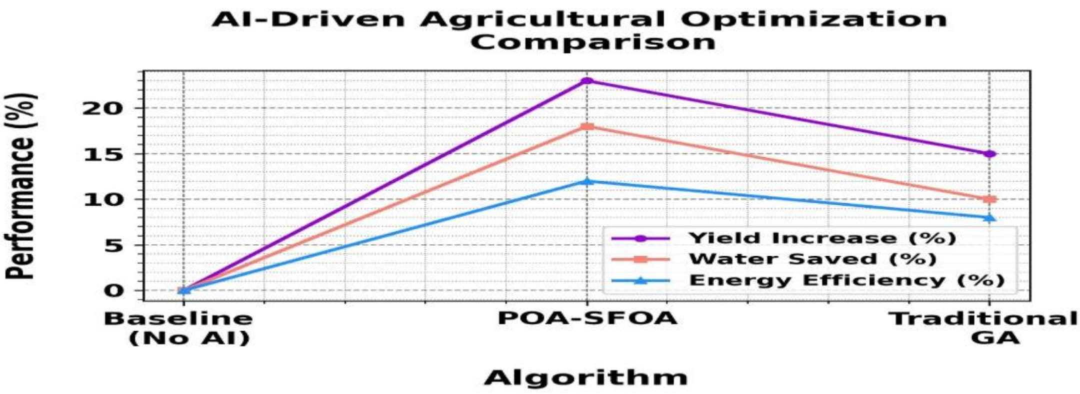

Figure 9: Comparative Analysis of AI Algorithms for Enhancing Hydroponic Efficiency

Figure 9 presents the research that investigates the merits of ML algorithms in optimizing crop production through hydroponics, focusing on increased yield, competitive water conservation, and improved energy efficiency. The baseline system nor AI will show improvements in key performance indicators. The hybrid POA-SFOA software release demonstrated achievement with returns of a 23% increase in yield, 18% water savings, and 12% energy efficiency improvement. By contrast, the traditional genetic algorithms yielded modest gains: a 15% increase in yield, 10% water savings, and 8% energy efficiency. These results point to a better optimization capability of POA-SFOA in controlling environmental parameters such as pH, light intensity, and nutrient flow. Decision-making has to be done using AI so that the production or crop systems can have optimum growth and be sustainable and resource-efficient. Such decision-making will also pave the method for smart agriculture of the future in resource-constrained environments.

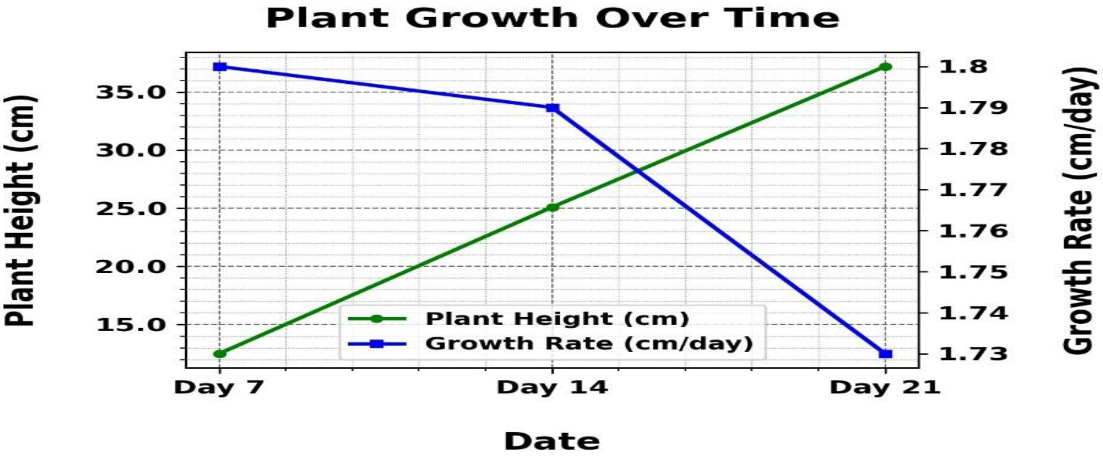

Figure 10: Smart IoT-Based Hydroponics for Sustainable Crop Growth

Figure 10 presents an IoT-based automated monitoring system for hydroponics, which has been designed to optimize crop development and enhance sustainability. Real-time data on pH, temperature, humidity, light intensity, and water level were collected by integrated sensors and analyzed on a cloud platform. Growth performance was assessed concerning measurements of plant height and growth rate. During the observation period of 21 days, plant height increased from 12.5 cm on Day 7 to 37.2 cm on Day 21, with corresponding growth rates from 1.8 to 1.73 cm/day. The precision of the system allowed for modifying environmental parameters on time to promote nutrient uptake and water efficiency. An ML algorithm was used for predictive analyses and control optimization to improve resource use and minimize manual interventions. These results indicate that IoT-enabled hydroponic automation can substantially increase crop yield, endorse sustainable practices, and present a scalable solution for modern agricultural systems with land and water constraints.

Table 4: Comparative Evaluation of Hydroponic Systems Based on Key Performance Parameters

Parameter	Traditional Hydroponics	Semi-Automated Hydroponics	Proposed IoT-Based Method
Crop Yield Increase	Baseline (0%)	+10–15%	+25–30%
Water Usage Efficiency	~60%	~75%	~90–95%
Nutrient Optimization Accuracy	Low (~50%)	Moderate (~70%)	High (~92%)
Energy Consumption	High	Moderate	Optimized with Automation
Labor Requirement	High (Manual)	Moderate	Low (Automated)
Real-Time Monitoring	No	Partial	Yes (24/7 IoT Monitoring)
Adaptability to Environmental Change	Low	Moderate	High (via MAMFGAT)
Return on Investment (ROI) Time	2–3 years	1.5–2 years	<1.5 years (due to higher yield and savings)

Table 4 shows the hydroponic IoT system showcases definite superiority over conventional and semi-automated systems on all major agricultural efficiency parameters; the proposed system increases crop yield by about 25-30% as compared to 10-15% for the semi-automated and baseline yield for the traditional methods. Water-use efficiency improves maximally to 90-95%; nutrient optimization accuracy reaches up to 92% with data-driven control. The proposed system, unlike traditional ones, ensures energy efficiency and reduced manual labour; instead of using manual labour to monitor and uphold the hydroponic system, it only requires monitoring interventions by human operators. MAMFGAT allows real-time monitoring 24/7, which uses environmental adaptability to optimize the environment for crop growth adjustment. With the high startup costs, a return on investment can be realized in less than 1.5 years with increased yields and resource savings, securing a sustainable and efficient pathway for modern agriculture.

RESEARCH CONCLUSION

The research on enhancing hydroponics efficiency using an IoT-based automated monitoring and sustainable crop production system demonstrated significant improvements in both crop yield and resource management. By integrating IoT sensors to monitor key environmental factors such as temperature, humidity, pH levels, and nutrient concentrations, the system allowed for real-time tracking and precise control of growing conditions. Automation, powered by predictive models and ML algorithms, enabled the system to make timely adjustments to factors like irrigation, nutrient delivery, and climate control, optimizing conditions for plant growth while reducing human intervention. The outcomes showed that this IoT-based approach not only led to higher crop yields but also substantially reduced water and nutrient waste, making the hydroponic system more resource-efficient and sustainable compared to traditional methods. Moreover, the system's ability to predict crop needs and make data-driven decisions allowed for more accurate and efficient management of resources, contributing to enhanced sustainability in urban farming practices. The use of renewable energy sources, such as solar power, further supported the sustainability of the system by reducing its environmental impact. Overall, the study confirms that IoT-based automation holds great potential for revolutionizing hydroponic farming by improving efficiency, promoting sustainability, and providing a scalable solution to meet the rising demand for food production in urban environments. Future research could focus on further optimization of the system, including the integration of advanced AI techniques and the exploration of additional sustainable practices for crop production.

REFERENCES

1. Tatas, K., Al-Zoubi, A., Christofides, N., Zannettis, C., Chrysostomou, M., Panteli, S. and Antoniou, A., 2022. Reliable IoT-based monitoring and control of hydroponic systems. Technologies, 10(1), p.26.
2. Kour, K., Gupta, D., Gupta, K., Anand, D., Elkamchouchi, D.H., Pérez-Oleaga, C.M., Ibrahim, M. and Goyal, N., 2022. Monitoring ambient parameters in the IoT precision agriculture scenario: An approach to sensor selection and hydroponic saffron cultivation. Sensors, 22(22), p.8905.
3. Mamatha, V. and Kavitha, J.C., 2023. Machine learning-based crop growth management in greenhouse environment using hydroponics farming techniques. Measurement: Sensors, 25, p.100665.
4. Priya, G.L., Baskar, C., Deshmane, S.S., Adithya, C. and Das, S., 2023. Revolutionizing holy-basil cultivation with AI-enabled hydroponics system. IEEE Access, 11, pp.82624-82639.
5. Taha, M.F., ElMasry, G., Gouda, M., Zhou, L., Liang, N., Abdalla, A., Rousseau, D. and Qiu, Z., 2022. Recent advances of smart systems and internet of things (iot) for aquaponics automation: A comprehensive overview. Chemosensors, 10(8), p.303.
6. Fuentes-Peñailillo, F., Gutter, K., Vega, R. and Silva, G.C., 2024. New generation sustainable technologies for soilless vegetable production. Horticulturae, 10(1), p.49.
7. Untoro, M.C. and Hidayah, F.R., 2022. Iot-based hydroponic plant monitoring and control system to maintain plant fertility. INTEK J. Penelit, 9(1), p.33.
8. Diaz-Delgado, D., Rodriguez, C., Bernuy-Alva, A., Navarro, C. and Inga-Alva, A., 2025. Optimization of Vegetable Production in Hydroculture Environments Using Artificial Intelligence: A Literature Review. Sustainability, 17(7), p.3103.
9. Songneam, N., Siringam, T. and Rattanasuwan, S., 2024. Development of Hydroponics Lettuce Production Process to Increase Productivity and Quality using Automated Control System via Internet of Things (IoT) Technology.
10. Booneua, W., Chai-Arayalert, S. and Boonnam, N., 2022. Automated Hydroponics Notification System Using IOT. International Journal of Interactive Mobile Technologies, 16(6).
11. Anjaiah, M., Mohan, B., Sainadh, B.P. and Vardhan, K., FABRICATION AND DEVELOPMENT OF IOT BASED MONITORING SYSTEM FOR HYDROPONICALLY GROWN PLANT.
12. Kadam, S.A., Kadam, P.S. and Mohite, D.D., 2024. Design and experimental analysis of a closed-loop autonomous rotary hydroponics system for revolutionizing fenugreek yield and enhancing food security. Discover Sustainability, 5(1), p.137.
13. Sangeetha, T. and Periyathambi, E., 2024. Automatic nutrient estimator: distributing nutrient solution in hydroponic plants based on plant growth. PeerJ Computer Science, 10, p.e1871.
14. Patel, J., Bhatt, T. and Joshi, A., 2024, August. IoT-Driven Enhancement of Hydroponic Fertilization Efficiency Through Machine Learning: A Data-Centric Strategy. In 2024 Second International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI) (pp. 298-302). IEEE.
15. Duangpakdee, K. and Sukpancharoen, S., 2024, July. Vertical Smart Farm System for Off-Season Crop Production using Hydroponics and IoT-based Environmental Control. In 2024 International Conference on Advanced Robotics and Mechatronics (ICARM) (pp. 284-289). IEEE.
16. Al-Gharibi, R.S., 2021, July. IoT-based hydroponic system. In 2021 International Conference on System, Computation, Automation and Networking (ICSCAN) (pp. 1-6). IEEE.
17. Ragaveena, S., Shirly Edward, A. and Surendran, U., 2021. Smart controlled environment agriculture methods: A holistic review. Reviews in Environmental Science and Bio/Technology, 20(4), pp.887-913.
18. Mamatha, V. and Kavitha, J.C., 2023, April. Remotely monitored web-based smart hydroponics system for crop yield prediction using IoT. In 2023 IEEE 8th International Conference for Convergence in Technology (I2CT) (pp. 1-6). IEEE.
19. Paul, K., Chatterjee, S.S., Pai, P., Varshney, A., Juikar, S., Prasad, V., Bhadra, B. and Dasgupta, S., 2022. Viable smart sensors and their application in data-driven agriculture. Computers and Electronics in Agriculture, 198, p.107096.
20. Pagaduan, L.J., Tenebroso, E., Acanto, E., Jean, R., Allado, E., Ernesto, C., Santos, E., Carlo, F., Cruz, E., Dela, I.G. and Baylon, E., 2024. Automated Hydroponic Farming System Using Nutrient Film Technique. Riza Jean and Allado, Engr. Ernesto C. and Santos, Engr. Francis Carlo and Cruz, Engr. Ivy Gail Dela and Baylon, Engr. Carl Steven, Automated Hydroponic Farming System Using Nutrient Film Technique (July 20, 2024).
21. Joshitha, C., Ranga, B.P. and Reddy, B.H., 2025, January. A Sensor-Driven Automated Hydroponic System for Optimized Plant Growth in Diverse Environments. In 2025 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE) (pp. 1-7). IEEE.
22. Hanafi, A.M., Hussien, S.A., Elnahal, D.H., Ahmed, S.E.H., Salem, M.A., Zainhum, A.R., Elsayed, A.A., Ibrahim, M.A. and Abdel Sattar, Y.S., 2025. Revolutionizing Agriculture with IoT, Mobile Apps, and Computer Vision in Automated Hydroponic Greenhouses. International Journal of Engineering and Applied Sciences-October 6 University, 2(1), pp.1-16.

23. Rofiansyah, W., Zalianty, F.R., La Ito, F.A., Wijayanto, I., Ryanu, H.H. and Irawati, I.D., 2025. IoT-based control and monitoring system for hydroponic plant growth using image processing and mobile applications. PeerJ Computer Science, 11, p.e2763.
24. Dutta, M., Gupta, D., Juneja, S., AlNadhari, S. and Belhaouari, S.B., 2025. Machine learning insights for sustainable hydroponic cultivation and growth monitoring of allium cepa using smart hydro kit. Scientific Reports, 15(1), p.10164.
25. Catota-Ocapana, P., Minaya-Andino, C., Astudillo, P. and Pichoasamin, D., 2025. Smart control models used for nutrient management in hydroponic crops: a systematic review. IEEE Access.
26. Aurasopon, A., Thongleam, T. and Kuankid, S., 2024. Integration of IoT Technology in Hydroponic Systems for Enhanced Efficiency and Productivity in Small-Scale Farming. Acta Technologica Agriculturae, 27(4), pp.203-211.
27. Varghese, A.B. and Deepika, M.P., 2024, August. Enhancing Hydroponic Production: A Review of Plant Growth and Health Monitoring System. In 2024 Second International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI) (pp. 492-498). IEEE.
28. Khadijah Febriana, R., Thakur, R. and Roy, S., 2024. Enhancing Hydroponic Farming Productivity Through IoT-Based Multi-Sensor Monitoring System. In IoTBDS (pp. 351-357).
29. Naresh, R., Jadav, S.K., Singh, M., Patel, A., Singh, B., Beese, S. and Pandey, S.K., 2024. Role of hydroponics in improving water-use efficiency and food security. International Journal of Environment and Climate Change, 14(2), pp.608-633.
30. Rajaseger, G., Chan, K.L., Tan, K.Y., Ramasamy, S., Khin, M.C., Amaladoss, A. and Haribhai, P.K., 2023. Hydroponics: current trends in sustainable crop production. Bioinformation, 19(9), p.925.