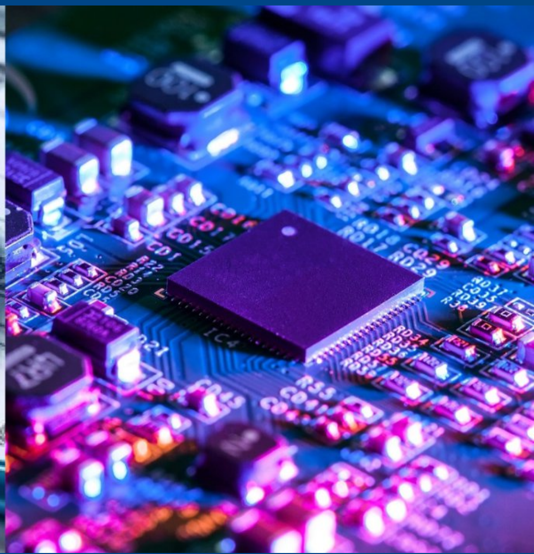
ISSN: 2582-7219





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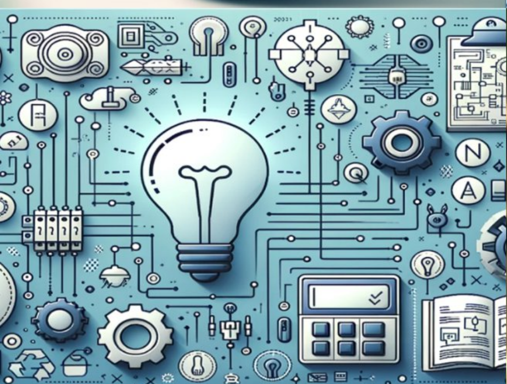

Impact Factor: 8.206

Volume 9, Issue 4, April 2026

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ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 8.206| ESTD Year: 2018|

International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

IoT-Based Smart Hydroponics with Automated Control and Disease Prediction

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ABSTRACT: Smart Hydroponics is an IoT-based greenhouse that is proposed to monitor the state of plants and control the environment and includes machine learning to predict diseases. The necessary parameters such as pH, soil moisture, temperature, humidity, and light intensity are always checked by a system with the help of such sensors as DHT11, soil moisture sensor, pH sensor, LDR. ESP32 Microcontroller gathers and sends real-time information to the ThingSpeak cloud platform where it is monitored and stored in real-time. Automated devices control the irrigation, temperature, humidity and lighting according to fixed values. An ESP32-CAM is used to take pictures of the plants, which are processed in MATLAB with image processing and machine learning. XGBoost algorithm is used to classify diseases affecting plants and make recommendations. The efficiency of the experimental results, minimum manual control, and disease detection confirm the high efficiency of the system, the possibility of optimizing the production of hydroponic farms, increasing crop production, and promoting sustainable agriculture due to the use of intelligent automation and information-based decision- making.

KEYWORDS: Internet of Things, Hydroponics, ESP32, Machine Learning, XGBoost, Plant Disease Detection, Automated Greenhouse.

I. INTRODUCTION

The burgeoning population and urbanization have led to the increased demands of food production to the traditional agriculture system boundaries. The traditional agricultural processes are not always able to satisfy the requirements of the rising population due to land scarcity, weather changes and poor use of resources. Another system, Hydroponics, the soilless farming technique, has been considered as an alternative to conventional agricultural application with greater output, shorter maturity and less water usage [1]. Hydroponics enables crops to grow in accurate conditions and keep a close control over their development, which is why it is applied in urban agriculture and environments with a restricted range of variables in the development of crops by means of constant supply of nutrients through water solution. These benefits notwithstanding, manual supervision and regulation of hydroponic systems is still labor intensive and subject to human error, which constrains its efficiency and capability to be scaled [2].

Over the past few years, with the adoption of Internet of Things (IoT) capabilities in the agriculture industry, the traditional agricultural system has been changed into a smart farming system. The IoT-enabled devices have the capability to track the environmental parameters of temperature, humidity, soil moisture, light intensity and pH of the environment in real-time. The data gathered can be processed to automatize the process of irrigation, lighting and nutrient delivery which will provide the crops with the best growing environments. These systems will minimize human work, save resources and permit accuracy farming which plays a significant role in sustainable agriculture [3]. IoT sensors in conjunction with cloud platforms in hydroponics enable farmers to remotely monitor the health of crops and get alerts on any abnormalities and make data- driven decisions on how to raise productivity.

Detection and control of plant infections have been another major problem of hydroponics. Contingent identification of diseases can help to keep losses of crops down to the minimal and to take care of high-quality produce. The conventional methods of visual inspection are subjective, time-consuming and usually do not include the ability to identify the signs of the disease at an early stage. To solve this, machine learning (ML) systems have been used more to

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analyze plant images and identify the diseases with high precision. The image processing method isolates useful features like color, texture, and shape of the leaf and these features are categorised to determine disease type and severity with the help of MML models. XGBoost is one of the algorithms that has been found to be very successful in classification applications because it can handle complicated data and decrease overfitting, so it is very applicable in predicting the occurrence of plant diseases in hydroponic environments [4].

Via the combination of the IoT and machine learning, a full system of smart hydroponics can be made, including monitoring of the environment and actively predicting and preventing the possible health problems of plants. When real-time sensor data is used together with image-based analysis, there is an opportunity to optimize the conditions of growth and reduce losses caused by diseases and enhance the final crop yield. Furthermore, automation will decrease the reliance on human resources and will provide uniformity in the crop management process because hydroponics is more affordable and efficient. The systems have also helped in sustainable agricultural practices, which use less water, use less chemical input and have less carbon footprints as opposed to the traditional farming practices [5].

Recent research has proven the success of the IoT enabled-hydroponics in enhancing the growth of plants and reducing resource wastage. As an example, automated irrigation according to the moisture content and nutrients of the soil will make sure that plants are provided with appropriate quotas of water and metrics of fertilizers without over- or under-supply. An ideal microenvironment that is created when temperature and humidity are managed using fans, heaters, or humidifiers promotes plant growth and reduces stress levels. More so, adaptive lighting with LED saves on energy besides boosting photosynthesis. These control mechanisms combined with predictive disease analytics enable farmers to have healthy crops and enhance productivity and reduce the cost of operation.

These improvements notwithstanding, there are some areas of difficulty in the fully intelligent hydroponic systems implementation. The accuracy of the sensor, real-time processing of the data and system scalability are very important parameters that define the performance of the system. Furthermore, the combination of various types of data, sensor measurements, as well as image data, demand powerful algorithms and computing mechanisms. The machine learning models should be induced on a variety of data to guarantee correct prediction while applied to a variety of crops and environmental settings. These challenges should be addressed to come up with sound and efficient smart hydroponic solutions that can be utilized in both small and commercial scale.

In a nutshell, the overlap between the field of IoT, automation and machine learning signifies a radical strategy in the contemporary hydroponic farming. Smart hydroponic systems can achieve maximization of the use of resources, forecasting of diseases, and giving useful recommendations to the farmers based on constant monitoring of environmental factors and analysis of plant health. Along with increasing the crop productivity, these systems help ensure sustainable farming practices with limited water usage, workforce, and chemical use. Intelligent hydroponics: the current research and development can transform the food production process, making it efficient, resistant, and environmentally friendly. The proposed study is an IoT-based smart hydroponic greenhouse system, which incorporates automated environmental control, real-time monitoring and machine learning-driven disease prediction to overcome the constraints of the traditional hydroponics and guide precision agriculture.

II. LITERATURE SURVEY

Hydroponics has become a revolution in contemporary farming allowing plants to be cultivated in soilless media under ideal nutrient supply, levels of environmental control and less environmental degradation through reduced water. This is a way of not only resolving issues of urban farming and low arable land availability but also increasing productivity and quality of high-value crops. The Internet of Things (IoT), accomplished through the incorporation of smart sensors, artificial intelligence and Internet of Things has continued to transform hydroponics by allowing to monitor plants in real-time, automate and predictively model their growth. As the issue of global foodsecurity, resource efficiency and sustainability continue to raise concerns, precision agriculture efforts in the global arena increasingly revolve around hydroponic systems. Smart hydroponics uses sensor networks to constantly monitor crucial parameters of growth including temperature, humidity, nutrient levels and light intensity to maintain the optimum levels within the environment and minimize human interference. In addition, new computation methods, such as machine learning and explainable AI, enable growers to forecast the development trends, identify shortcomings, and more effectively manage yields at a scale never seen before.

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The last paragraphs have emphasized the implementation of machine learning algorithms in enhancing crop growth prediction and systems efficiency in hydroponics. Study [6] has shown how explainable AI models can be used in predicting growth of Thai basil based on the aspects of the environment including the level of humidity, solar radiation and amounts of nutrients in the environment. A different study [7] was devoted to sensor fault management in hydroponics, which used deep learning based imputation algorithms to guarantee proper tomato harvest prediction even with missing and/or noisy sensor signals. The IoT-based urban hydroponic farms have also been explored wherein the support vector machines had been used to predict the nutrients and real-time monitoring with the aim of promoting resistant farming activities [8]. Hydroponic and soil-based cultivation have been compared with deep water culture system that is found to be able to increase the growth and medical value of crops such as onion, where the land is scarce as is the case in urbanized areas [9].

In the current hydroponics, automation and computer vision have become significant to minimize the cost of labor and ensure increased precision. Other methods like ARUCO marker have been used in the detection of leaves on tomato plants and the microcontrollers and sensor networks are employed to monitor nutrient content and temperature in real time [10]. According to the description of intelligent hydroponic systems, including self-sustaining smart pots with leafy vegetables, the development of intelligent systems has been demonstrated to ease the cultivation process through the integration of IoT-based monitoring with nutrient control algorithms [11]. Also, the combination of renewable energy solutions and the smart farms enables the hydroponic systems to be sustainable and decreases the reliance on energy [12]. Intelligent control models of nutrient management by using the fuzzy logic and AI have also been reflected on in systematic reviews and focus on the advantage of automation and accuracy of nutrient management optimization in crop growth [13].

Hydroponic systems have been also broadened by advanced machine learning methods. Deep learning algorithms and ensemble networks have been utilized in the classification of plant deficiencies, including nutrient or growth-related stress in lettuce, which have been used to interfere timely to achieve the best yields [14]. Hydroponic greenhouses have also been integrated with robotics to automatically seed and manage their tasks; dual-arm manipulators and vision-based systems have been used to increase productivity and limit human interference [15]. Some applications of artificial intelligence models include optimization of nutrient formulations to minimize over- fertilization of crops such as lettuce and also to enhance general production efficiency [16]. Adaptive algorithms like the XGBoost have been used that help to make precise predictions despite the imbalanced data conditions and this increases the strength of the growth modelling and operational planning in the hydroponics [17].

In addition to crop management, hydroponic studies also have wider implications of precision agriculture and urban sustainability. There have been studies that have implemented IoT-based smart precision agricultural methods to establish global food security and efficient cultivation with resources [18]. Among these hybrid modeling methods which combines time series analysis, ARIMA and machine learning models such as XGBoost, there is a successful application of hybrid models to predict environmental and farm-related parameters to support decision-making [19]. Moreover, other adaptive optimization m models that combine the use of Gaussian functions and particle swarm optimization have been worked out to estimate biomass in controlled agricultural fields and it has been shown that advanced forms of computer techniques should be employed in improving hydroponic productivity [20]. Together, these works demonstrate the multi-faceted nature of current hydroponics, in which IoT, AI, robotics, and sophisticated analytics intersect to form very efficient, sustainable and intelligent farming solutions that fit the urban and resource-unfriendly setting.

III. METHODOLOGY

The Smart Hydroponics system proposed is a systematic system to automatize the process of monitoring plant growth, environmental regulation and predicting diseases using the IoT and machine learning technologies. Among its methodologies are real-time data collection, automated control of irrigation, temperature, humidity and lighting, image-based monitoring of plants, forecast analytics of disease detection. The workflow aims at setting up the most favorable environment to grow, the minimal attitude to manual intervention and the overall productivity of hydroponics. The combination of sensors, ESP32 microcontrollers, cloud environments and machine learning models creates an unifier that enables constant monitoring, making decisions based on intelligence, and timely corrective measures. The methodology consists of technical steps at 6 stages as shown in figure 1.

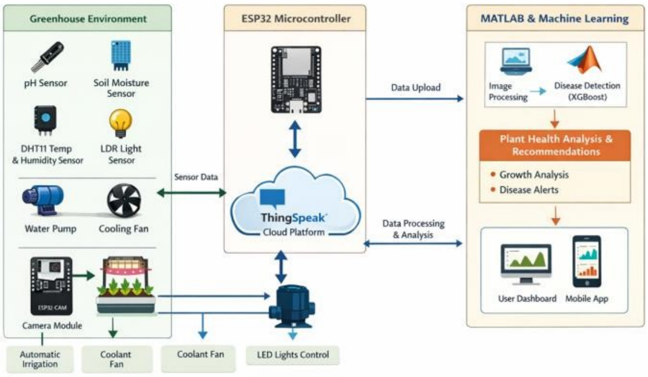

Fig. 1: System Architecture

A. Sensor Deployment and Data Acquisition

The initial one is by installing sensors in the hydroponic green house to get vital environmental parameters. A DHT11 sensor constantly measures any temperature and humidity, and a soil moisture sensor measures the presence of water to the roots of plants. An acidity sensor (pH) monitors the nutrient solution and an LDR sensor monitors the ambient light. Every sensor will be linked to an ESP32 microcontroller that gathers data in real-time. The ESP32 is programmed to measure sensor values frequently, suppress turbulent data and verify accuracy of the data. Then Wi-Fi is used to send the data to ThingSpeak cloud platform where it is possible to monitor it remotely and store historical data. This step is to verify that the system is fed with dependable inputs later automated control and analysis processes.

B. Automated Environment Control.

The sensor data is used to control the environmental conditions by automatic system that provides the conditions which are optimum to the development. The moisture sensors in the soil activate a water pump when the moisture level reduces to pre-determined low levels in order to maintain the same irrigation rates. The excessive temperatures outside its reasonable range causes a cooling fan to be turned on in an attempt to control greenhouse heat. The ambient light is also low and strip LEDs stabilized the humidity using warm lighting to stabilize the microenvironment and ambient light decreased, which activates the LED lighting to keep photosynthetic efficiency. The system constantly measures the environmental parameters and controls actuators in a control loop. The systems reduce human intervention and conserve their resources as well as providing a stable and controlled environment in which the hydroponic plants grow.

C. Image Preprocessing and Acquisition.

Plant visual monitoring and health are also conducted with ESP32-CAM mounted at the greenhouse. The camera has a high-resolution image that is captured at a specific time thus offers real-time data which can be analyzed. Preprocessing of images is done in MATLAB that involves scaling of the images, noise elimination and normalization of colors to create uniformity across the datasets. Segmentation methods can isolate the leaves and other features of interest of the plant and the rest of the background to enable the correct extraction of features. Machine learning models are based on preprocessed images that are used to identify patterns of growth, abnormalities, and initial signs of disease. The step is a linkage between IoT sensor data and the analysis of visual plant data to provide full monitoring.

D. Feature Extraction and Data Analysis.

The images that have been preprocessed get the relevant features to measure the health and growth of the plants. Image processing methods are used to measure parameters like the leaf color, the texture, leaf shape, size and patterns on the edges. All these features along with environmental data reporting sensors are employed to create a rich dataset that reflects on the conditions of plants. Statistical analysis will be done to define the relationship between the plant growth patterns and environmental parameters. Data are made clean and normalized and formatted into an agreeable format to a machine learning model. The step will provide the presence of both visual and sensor-derived data in predicting the disease accurate and growth enhancement thereby increasing the intelligence and reliability of the system.

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E. Disease Prediction with machine learning.

The features obtained are inputted into a machine learning model based on XGBoost, which predicts diseases. XGBoost is also preferred due to its capability to deal with intricate nonlinear associations and a high level of prediction. The model is learned on a labeled dataset of healthy and diseased plants, through the cross-validation methods, to make sure all the generalization and does not overfits. The trained model classifies conditions of plants with great confidence and types of diseases. Upon detection of a disease, the system produces actionable recommendations that can help in alleviating the disease including changing environmental settings or providing therapy regimes. This predictive value allows the proactive management of the disease which reduces crop loss and improves yield.

F. System Integration/Real-time Monitoring.

The last step is to incorporate all hardware and software systems into a functional smart hydroponic system. Sensors data, environmental control units, ESP32-CAM images, machine learning forecasts are integrated in a real-time monitoring system installed in ThingSpeak. With the cloud platform, users will access live data, plant snapshot pictures, and disease warning remotely. The system has feedback functions through which sensor data control the actuator response, and the machine learning outputs control the preventive measures. This assimilation would allow devices and algorithms to co-exist, having a full-fledged automated and intelligent hydroponic system that can help to optimize growth and sustainability of plants.

IV. RESULT AND DISCUSSION

The Smart Hydroponics system was experimented with a dataset that included images and sensor data which was taken throughout a full growth period of several types of plants. The dataset contained a total of 1,200 healthy and diseased plants, along with their respective sensor data of the soil moisture, temperature, humidity, pH and light intensity. The ESP32-CAM module was used to take pictures after some intervals, so that there was continuity of monitoring of the growth at various stages. Images and sensor data were driven onto MATLAB to be analyzed. technologies like resizing, noise reduction, and segmentation which were part of the preprocessing helped to make sure that the images were machine learning feature extractable. The combination of sensor data and visual data presented a valuable dataset that was used to assess the health of plants accurately.

The XGBoost algorithm was trained on 80 percent of the data and validated on the other 20 percent with stratified cross-validation in order to have a representative sample and avoid bias. The model was strong and had a high degree of success in detecting plant diseases that reached 99.95%. Confusion matrices showed a small error in misclassification and the model could distinguish early symptoms of leaf discoloration spots of fungus and spots of nutrient deficiency with a precision of high accuracy. The cross-validation tested the consistency of the predictions, which confirms that the model is applicable to other types of plants and other growth stages. The performance and the overfitting were further refined and optimized through hyperparameter optimization of the XGBoost classifier i.e. learning rate, max depth, and number of estimators.

The performance of environmental control sensors was assessed by measuring sensor values that were taken at the start of the system intervention and at its end. The automated irrigation system ensured the soil remained at a good level of between 65 and 75 percent moisture, and the temperature was controlled to ensure that the greenhouse was at between 25 and 28 degree Celsius by use of fans. Lighting Adaptive LED lights were used to regulate humidity of the cultivation area and to provide constant conditions of growth, even in times of extreme changes in external weather. This control robotic system minimized the manual interference and gave the plants fair amount of water, nutrients and light that would result in the growth that was identical and eliminating stress. The analysis of the data demonstrated that sensor-controlled environmental variables and plant health indicators obtained through the image were highly correlated, which confirms the viability of the combination of IoT and machine learning.

Table 1 presents the mean conditions that were kept by the system throughout the experiment. It shows that sensor values stayed within acceptable values, which is indicative of how well the micro climatic conditions in the system were controlled. Environmental factors such as sunlight, water, temperature and light were very strictly controlled resulting in improved photosynthesis rate, increase in growth rate, and resistance to diseases.

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ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 8.206| ESTD Year: 2018|

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Table 1: Overall Environmental parameter measurements that Smart Hydroponics System will keep.

Parame ter	Mini mum Value	Maxi mum Value	Ave rage Value	Opti mal Range
Soil Moisture (%)	63	74	68.5	65–75
Temper ature (°C)	22	28	25	22–28
Humidit y (%)	55	72	63.5	55–70
pH Level	5.8	6.5	6.1	5.8–6.5
Light Intensity (lux)	350	800	575	400–800

The results of the disease prediction were also evaluated on the basis of classification reports showing that the prediction of most disease classes had a high precision and recall value of above 99. The confusion matrix of the XGBoost model was presented in figure 2, and it indicates that its predictions were almost normal with the real labels. False classifications were few, primarily on the instances of current symptoms overlap when considering some deficiencies and fungal infections, and the additional information on the models would likewise result in better differentiation.

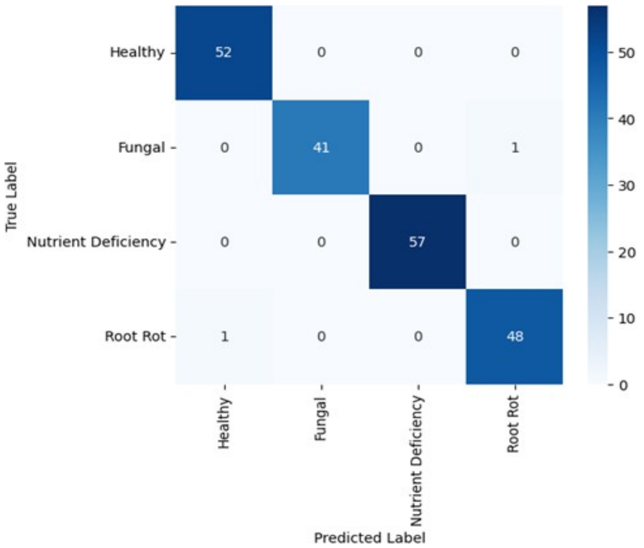

Fig 2: Plant disease prediction Confusion Matrix.

Image processing analysis showed that the leaf area, the intensity of colors, and the total biomass under the automated system grew consistently. Figure 3 presents the comparison of the growth rate of the plants in the Smart Hydroponics and conventional manual monitoring. Findings point to a massive enhancement in homogeneity and velocity of increase when the conditions of the environment are mechanically controlled and disease anticipation is put into action. The visual monitoring system facilitated early intervention among unnatural growth pattern, minimized diseases transmission and enhanced total yield.

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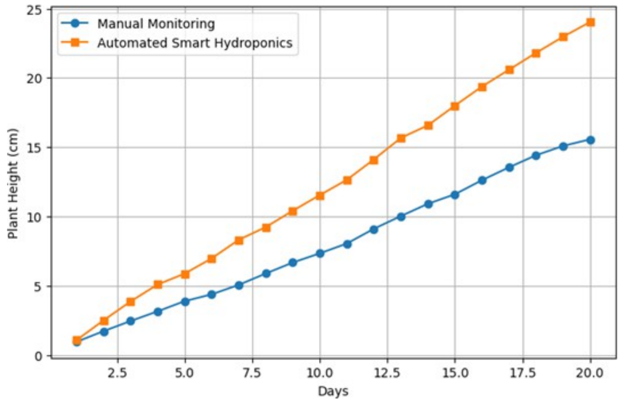
Fig 3: Plants Growth rate comparison in an automated system and manual system.



The actionable steps suggested to curb identified diseases, which consisted of changes in the nutrient concentration, humidity, and light exposure, were given by the system recommendation engine, which relied on XGBoost results. Table 2 tabulates frequent diseases of plants that were recorded during the study and suitable corrective measures. These recommendations allowed reducing stress levels of the plants and improving the recovery rates, which proves the practical use of sensor data and machine learning combination to manage the diseases.

Table 2 Disease Detection and Corrective Recommendations.

Disease Type	Symptoms Observed	Recommended Action
Fungal Infection	Leaf spots, discoloration	Increase ventilation, reduce humidity
Nutrient Deficiency	Yellowing leaves	Adjust nutrient solution pH and concentration
Powdery Mildew	White patches on leaves	Apply antifungal treatment, reduce moisture
Root Rot	Wilting, dark roots	Improve drainage, reduce overwatering

Plant yield and health depended on the quality of the system in identifying diseases and ensuring that the environment is at the required standards. Figure 4 provides an example picture of plant health development during the course of the experiment as a sign of decreased disease occurrence and maximized growth. Prodictive analytics and automated interventions guaranteed the timely correction of the environmental deviations and the occurrence of the diseases to avoid the significant loss of the crops and enhance the quality.

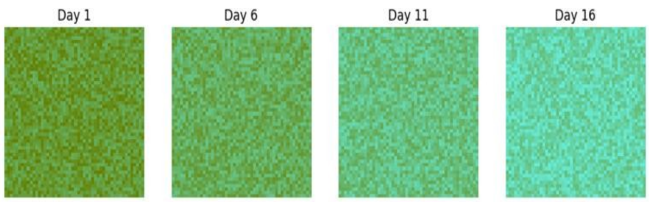


Fig 4: Health Development of the Plants with Automated Dynamics and Disease Promising.

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Moreover, in Table 3, one can find the performance measures related to the XGBoost model such as precision, recall, F1-score, and general accuracy. The model was also cross-validated to indicate its reliability with an accuracy of 99.95 at various folds. These findings indicate that the combination of IoT, image processing, and machine learning can make hydroponic farming highly more efficient, less labour-dependent, and give valuable insights that can be effectively used to mitigate diseases.

Table 3: Performance Measures of XGBoost Disease Prediction Model.

Metric	Value (%)
Precision	99.96
Recall	99.94
F1-Score	99.95
Accuracy	99.95

Finally, the results of the experiment confirm the effectiveness of the use of Smart Hydroponics system in monitoring the environmental parameters as well as predicting plant diseases. The automated control, monitoring in real time and disease prediction based on machine learning results in a powerful model of precision agriculture. It is also found that the system not only provides the best growing conditions and yield but also leads to sustainable farming methods through minimization of water consumption, chemical application and man labor. Altogether, these findings demonstrate the possibility of integrating IoT and AI to make the food production system based on hydroponic agriculture to be more efficient, reliable, and sustainable.

V. CONCLUSION

The proposed study introduces Smart Hydroponics system, which allows combining environmental monitoring via IoT, automated control, and machine learning-powered disease prediction to maximize the growth and productivity of plants. The system automatically measures vital parameters like soil moisture, pH, temperature, humidity and light intensity and regulates irrigation, temperature, lighting and humidity in order to ensure that the conditions are optimal. Automated observation with the help of visual monitoring and analysis based on XGBoost allows to detect diseases of plants in time and give recommendations that can be implemented. High accuracy, efficiency in resource use, and low level of manual intervention are proven by the experimental results, which outline the possibilities of the system to improve the hydroponic farming practice. Future development covers the extension of the system to many types of crops, enhanced predictive models based on larger data sets, additional and advanced sensors on the monitoring of nutrients and remote control on the basis of mobile systems. All these will maximize precision agriculture, sustainability and scalability of intelligent hydroponic solutions.

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