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Original Article

A Compendious Study on IoT-based Monitoring and Control System for Hydroponic System-Based Cultivation

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Abstract - *The hydroponic system involves cultivating plants in water with a nutrient solution. Various challenges may arise during plant growth in hydroponics. The integration of IoT has become a crucial trend in hydroponics. To address this, the paper proposes a system suitable for both small and large-scale hydroponic setups, aiming to monitor plant growth effectively. This study proposes an Internet of Things (IoT)-based method for observing and controlling a hydroponic system. The system integrates various sensors to monitor key factors such as temperature, humidity, nutrient levels, pH, and water levels. These sensors connect to a microcontroller or single-board computer, which collects and transmits the data to a cloud-based platform for storage and analysis. Users can remotely access and manage the data through a web or mobile application. The system also incorporates automated control, adjusting humidity, temperature, and nutrient levels based on sensor data and predefined criteria. The proposed system offers a comprehensive and efficient approach to regulating and monitoring hydroponic systems, with easy adaptability to different hydroponic conditions and setups. The paper validates the system's utility and feasibility through experiments and results.*

Keywords *- Cultivation, IoT, Hydroponic, Sensors.*

1. Introduction

In India, agriculture serves as the primary source of livelihood, occupying a substantial portion of the country's land, accounting for 60% of its total area. However, the agricultural landscape in India is transforming due to increasing industrial development, leading to changes in climate patterns [1]. Over the past 6500 years, temperatures have risen, and the emission of greenhouse gases has reached unprecedented levels, resulting in atmospheric CO2 concentrations not seen in the past 2 million years. The once milder summers have given way to intense heatwaves, with India experiencing a record temperature of 51.0 degrees Celsius in 2021. The repercussions of such extreme heat extend to health, agriculture, infrastructure, and overall stability. Climatological disasters like heatwaves also bring about drought and diseases, further exacerbating the challenges. These climate changes significantly impact the agricultural production process. Various soil-less methods have been developed for crop production in response to these challenges. Among these, hydroponic systems have gained popularity as the most widely used method for planting crops.

In such a system, utilizing mineral nutrition solutions dissolved in water, plants can be cultivated hydroponically, eliminating the need for soil. This highly effective and environmentally friendly form of agriculture allows for the controlled growth of various crops. Maintaining optimal environmental conditions for plants, including temperature, humidity, nutrient levels, and pH, is crucial for the success of hydroponic systems [1]–[3]. Traditionally, manual and labor-intensive monitoring and management have been necessary for hydroponic systems, potentially leading to reduced crop yields due to unpredictable growing conditions.

The advent of the Internet of Things (IoT) has introduced a more advanced approach, enabling the remote monitoring and automated control of hydroponic systems. The primary objective of this study is to develop an IoT-based model for monitoring and managing hydroponic systems. The research questions addressed in the study are as follows:

1.1. RQ1

How can an extensive and effective monitoring and control system for hydroponic systems be created using the IoT approach?

1.2. RQ2

What are the ideal sensor setups and communication protocols for a hydroponic monitoring and control system?

1.3. RQ3

In terms of crop productivity and environmental control, how does the suggested IoT-based system for hydroponic systems compare to conventional manual methods?

1.4. RQ4

What are the advantages and constraints of an IoT-based monitoring and management system for hydroponic systems?

This study aims to construct and develop an IoT-based system for hydroponic systems, evaluating its effectiveness through experiments and results to address the specified research questions.

Additionally, a comparative analysis with traditional manual methods for monitoring and managing hydroponic systems is conducted in this paper. The outcomes of this investigation will provide insights into how the IoT approach can enhance the efficiency and sustainability of hydroponic systems, potentially opening new avenues for agriculture in the future.

In summary, the paper introduces a novel approach to monitor and manage hydroponic systems using IoT technology—an innovative and rapidly advancing field with diverse applications, including agriculture. The proposed system seeks to overcome limitations identified in previous studies (as outlined in Section 2) by considering all crucial factors influencing plant growth and incorporating a robust algorithm for data analysis and prediction. The study's uniqueness lies in developing a comprehensive IoT-based model for monitoring and managing hydroponic systems, offering practical implications for sustainable agriculture.

The study is organized into six main sections. Section 1 covers the introduction, and Section 2 reviews relevant prior work. The approach for the proposed system is detailed in Section 3, while Section 4 discusses the experiments and results. Section 5 includes the discussion, and the conclusion and considerations for future research directions are presented in Section 6.

2. Literature Review

With an emphasis on increasing productivity, sustainability, and agricultural yields, the IoT approach is increasingly being used in agriculture. For example, the IoT approach can be utilized in the hydroponics system to monitor and regulate environmental factors, including pH, fertilizer levels, humidity, and temperature. By controlling the growth environment more precisely and consistently, crop yields can increase, and labour needs can decrease. IoT approach in hydroponic systems has been investigated in several studies. As an illustration, Alipio et al. [4] suggested an intelligent hydroponics system using a Bayesian Network (BN) to automate the process of crop growth. With the help of sensors, their approach keeps track of crop factors like pH, water temperature, Light Intensity (LI), and Electrical Conductivity (EC).

Additionally, BN trains for the prediction using the information gathered by the sensors. The hydroponic system is further controlled using the predicted values that were generated. The suggested approach achieved only 84.5% accuracy. A system that regulates and watches over the water circulation for crop growth was suggested by Nurhasan et al. [5]. The suggested approach for hydroponic systems uses Density-Functional Theory (DFT) principles. They utilized the Raspberry Pi microcontroller for communicating with the sensors. This suggested approach applies fuzzy Sugeno to train the collected data and keep track of key crop indicators like pH, temperature, and water content in the hydroponic tank.

A hydroponic fertilizer control system based on IoT was proposed by Adidrana et al. [6]. The authors in their study suggested a Non-Fungible Tokens (NFT)-based system. The composition of nutrient solutions is predicted in their study using a K-Nearest Neighbour (KNN) based approach. Additionally, in the suggested system, the microcontroller turns the nutrient controller on and off using prediction data. The accuracy of the suggested system was only 93%. An approach to smart hydroponic farming that makes use of physical and social strategies was used by Sisyanto et al. [7]. To monitor plant growth, the authors monitored factors such as pH, LI, temperature, and EC.

The proposed system's microcontroller, Raspberry Pi, is in charge of connecting to sensors and using Telegram BOT to track the growth of plants in real time. Deep Neural Networks (DNN) were used by Mehra et al. [8] for an IoT-based hydroponics system. An agricultural system for the tomato crop is created in their study. Using sensors, the author's study gathered more than 10,000 actual hydroponic farm data points, such as temperature, pH, LI, and water level. The actions required to regulate a hydroponic system were performed using a DNN model that the authors developed on the collected data. The proposed system was constructed by the authors using a tomato crop. The outcomes might not be as precise if this system is used to cultivate any other hydroponic plant. A model for the automated hydroponics system utilizing IoT was put forth by Asawari et al. [9]. The authors of this work created a system to collect real-time information on temperature, humidity, and pH for plant growth. The proposed system uses an ATMEGA2560 microcontroller to capture data. The growth of the plant is affected by several different factors. Only a few plant growth factors were considered by the proposed approach. Sethavidh et al. [10] suggested an IoT-based hydroponic farm-based predictive system for lettuce crop quality. The authors use the system for a lettuce crop in their study. The hydroponic environmental parameters for lettuce development in the suggested system include temperature, relative humidity, and LI.

The authors used Support Vector Regression (SVR), Multiple Linear Regression (MLR), and Artificial Neural Network (ANN) approaches in the system's training. However, feature selection using Machine Learning (ML) for the proposed system has not yet been implemented. An

IoT for hydroponic-style smart farms was suggested by Pitakphongmetha et al. [11]. The system that is suggested in their study takes into account the hydroponic plants' temperature and light requirements. The proposed system uses Wireless Sensor Network (WSN) to transmit the gathered data to the cloud. The authors trained the data for decision-making using fuzzy logic. Unfortunately, the sensors for the suggested systems' use in public have not yet been produced.

Using the IoT, Changmai et al. [12] presented a smart hydroponic lettuce farm. The authors thought of lettuce as a testing crop for the system. The suggested system automatically regulates the water's nutrition solution concentration. Additionally, the suggested approach controls the importance of air humidity for plant growth. Unfortunately, when applied with just a few plant growth characteristics, the proposed approach was not as accurate as expected. A fully automated hydroponic system for growing indoor plants was suggested by Palande et al. [13]. The suggested system maintains the conditions necessary for the growth of the plants. The proposed system took a few growth-related aspects into account. In the suggested system, some crucial plant growth factors are not taken into account.

Studies conducted on the application of IoT in hydroponic systems have concentrated on tracking and managing numerous environmental factors that affect plant development. Temperature, humidity, nutritional concentrations, pH, and LI are some of these variables. For data analysis and prediction, the majority of studies used various algorithms such as BN, Fuzzy Sugeno, KNN, DNN, and ANN.

The studies, however, have limitations regarding the factors taken into account for plant growth and the precision of the suggested systems, as shown in Table 1. In addition, there is limited relevance to other crops because some studies only took a small number of plant growth characteristics into account, while others concentrated solely on one particular crop. The proposed systems' accuracy also fluctuates and is not always as good as anticipated. The lack of an all-inclusive model that considers all crucial aspects of plant growth and offers high accuracy is the area of research that must be filled in these studies. Furthermore, a system adaptable to various crops and growing conditions is required. To bridge these gaps, this study suggests a system for monitoring a hydroponic system using an IoT approach that considers all the critical factors affecting plant growth and employs a reliable algorithm for data analysis and prediction.

Table 1. Literature Review

Studies	Findings	Metrics
Alipio et al. [4]	There are several considerations regarding the proposed approach. Firstly, relying on cameras for real-time video streaming may necessitate a stable and high-speed internet connection, which might not be consistently available in certain areas. Additionally, implementing deep learning through image processing could demand substantial computational resources, making it impractical in low-resource settings. Moreover, collecting larger datasets over extended periods might pose challenges regarding resources and feasibility in specific situations. The utilization of higher microprocessors and wireless connections could also escalate implementation costs, potentially making it unaffordable for small-scale farmers. Lastly, while personalized mobile applications could prove beneficial for remote monitoring, they may require training and technical support that might not always be accessible in certain communities.	84.53% (Accuracy)
Nurhasan et al. [5]	The study is constrained by its focus on a specific crop, lacking a comprehensive analysis of all essential factors influencing plant growth. Moreover, the system's efficacy may fluctuate under diverse growing conditions and alternative hydroponic methods. Consequently, additional research is imperative to investigate the technology's potential in broader applications and with different crops.	---
Adidrana et al. [6]	One limitation of the study is its reliance on a prototype scale, potentially lacking representation for larger-scale hydroponic systems. The efficacy of the KNN classification algorithm in larger systems may deviate from the observed prototype results, and the actuator module could encounter additional challenges when managing a greater number of nutrients. Furthermore, while the research suggests that increasing experiments with more data in diverse conditions can enhance system accuracy, the timeframe required to gather sufficient data for a substantial accuracy improvement remains unclear. The implementation cost of the IoT system on a larger scale, along with ongoing maintenance and data collection, may pose limitations for some growers. Lastly, it is essential to note that the study specifically focused on classifying nutrient conditions. It did not address other crucial factors for plant growth, such as temperature and light levels, which may also necessitate monitoring and control in a larger hydroponic system.	93.33% (Accuracy)

Sisyanto et al. [7]	One constraint of this study is the installation of only two out of the intended four sensors. The absence of pH and EC sensor modules has the potential to affect the precision of nutrient measurements and monitoring, possibly influencing the growth and yield of hydroponic crops. Moreover, the study relies on an internet connection for monitoring hydroponic crops, which may not be accessible in certain areas or may entail supplementary costs. Another limitation involves the necessity for additional output from relays, such as humidifiers, to enhance moisture. Additionally, the study does not integrate camera modules for visual monitoring of plant growth, which could offer valuable insights into crop health and development. In conclusion, future research endeavors could address these limitations by integrating extra sensors, exploring alternative monitoring methods, and expanding the system's output capabilities.	¦
Mehra et al. [8]	The proposed research has several limitations. Firstly, implementing a deep neural network for hydroponic plants can be challenging and time-consuming, given the extensive data processing and training requirements. Secondly, cultivating various types of hydroponic plants in separate tanks might demand significant space and investment, posing a potential limitation for certain growers. Additionally, acquiring a diverse range of hydroponic plants for growth and data collection in a single location could be challenging. Lastly, the proposed research does not address potential challenges associated with scaling up the system for larger commercial operations or the cost-benefit analysis of implementing such a system.	¦
Asawari et al. [9]	While the automated hydroponic system with IoT offers numerous advantages, it is not without its limitations. Firstly, the initial setup cost can be prohibitively high, particularly for small-scale farmers. Secondly, the system's reliance on a stable and reliable internet connection for remote monitoring and control may pose challenges in regions with limited connectivity. Thirdly, the system's susceptibility to technical failures or malfunctions due to its reliance on technology could impact crop yields. Additionally, effective operation and maintenance may necessitate specialized knowledge and training, presenting a challenge for certain users. Lastly, despite being an efficient and sustainable method, hydroponic farming still requires a substantial amount of energy to power the system, potentially posing limitations in areas with scarce or expensive energy resources.	¦
Sethavidh et al. [10]	This research's limitation is the absence of Feature Selection in constructing the machine learning model, potentially hindering the accuracy of the results. Furthermore, external factors like wind, sunlight, and temperature influenced the growth and behavior of the lettuce plants, introducing variability in measurements and potentially contributing to errors in the model's learning process. Consequently, the model did not achieve satisfactory learning outcomes. Future research avenues could investigate the implementation of Feature Selection to enhance the machine learning model's accuracy and explore strategies to minimize the impact of external factors on plant growth and behavior.	¦
Pitakphongmetha et al. [11]	This study's limitations include the absence of detailed information on the specific sensor technology utilized and the research's limited scope. While the study identifies various challenges in the agricultural domain, it falls short of presenting a comprehensive solution to address them. Furthermore, the absence of testing in a real-world scenario may limit the applicability and effectiveness of the study's findings.	¦
Changmai et al. [12]	Several limitations must be acknowledged in this study. Firstly, the research has been exclusively conducted in one location during the rainy season, raising questions about the generalizability of the results to other locations or seasons. To ensure the robustness of the findings, it is imperative to replicate the study in diverse locations and across different seasons. Secondly, the study exclusively concentrates on the growth of hydroponic lettuce, neglecting other crops and factors that could influence the overall productivity and profitability of a smart hydroponic farm. Thirdly, the upfront costs associated with deploying IoT devices and sensors might pose a financial challenge for small-scale farmers. It is crucial to develop more affordable and cost-effective IoT devices and sensors accessible to small-scale farmers. Lastly, the study solely delves into the technical aspects of the smart hydroponic farm, overlooking the social, economic, and policy implications of this technology. Further research is warranted to comprehend the impact of smart hydroponic farming on local communities and the broader agricultural sector.	¦
Palande et al. [13]	Nevertheless, there are potential limitations that can be inferred from the information provided. For instance, whether the study was conducted under controlled conditions or exposed to external factors such as weather changes or other environmental variables remains unclear. Moreover, the study's exclusive focus on one type of plant raises questions about the generalizability of the results to other plant types. The comparison between the plant grown in the system and the one grown outside the system may not provide a comprehensive assessment. Additionally, the reproducibility of the study's results in different settings and the system's scalability for commercial use are uncertain. Further research would be necessary to address these potential limitations and ascertain the broader applicability and feasibility of the presented system.	¦

3. Empirical Study

The proposed IoT-based monitoring system for hydroponic systems comprises multiple components collaborating to achieve the intended outcomes. The three primary components of the system include sensors, IoT devices, and control systems.

3.1. Sensors

Within a hydroponic system, sensors play a crucial role in gathering data on various environmental factors impacting plant growth, as outlined in references [14], [15]. Variables such as temperature, humidity, nutrient content, pH, and water content are among those monitored. Subsequently, the IoT devices linked to these sensors facilitate the transmission of collected data to the control system. The sensors utilized in this study are detailed in Table 2.

3.2. IoT

The IoT components utilized in this system are responsible for collecting data from the sensors and transmitting it to the control system, as referenced in [16], [17]. These IoT components can encompass sensors, other elements, microcontrollers like the Raspberry Pi, or similar IoT devices with analogous functions. The IoT devices employed in this system must possess the necessary interfaces to establish a connection with the sensors and effectively communicate data to the control system. For this study, an ESP8266 board with Wi-Fi connectivity has been chosen.

3.3. Control System

As the core component of the proposed system, the control system oversees and manages the hydroponic system based on information gathered from sensors and IoT devices [18], [19]. This system can be constructed using a computer or a comparable device capable of processing data, making decisions, and managing various aspects of the hydroponic setup. Processing data from IoT devices and sensors using models and algorithms, the control system could employ methodologies like Support Vector Machines (SVM), Fuzzy Logic, KNN, DNN, or similar approaches. The system utilizes these algorithms and models to anticipate the hydroponic system's environment and manage various system elements, including pumps and nutrient controls, to provide optimal plant growing conditions.

Furthermore, the control system can be configured to alert the user to environmental changes influencing plant development and to oversee and control the hydroponic system. For instance, if the temperature in the hydroponic system drops below a predetermined level, the control system may send a notification to the user, providing information about the issue and suggesting the best course of action. In this study, the control system employs a closed-loop control algorithm. The sensor data regulates hydroponic system parameters, such as pH and nutrient concentration. For this purpose, a Proportional Integral Derivative (PID) control algorithm is utilized, known for its effectiveness in maintaining control system stability [20]. The PID algorithm continuously adjusts system parameters based on sensor readings, ensuring optimal growth conditions for the plants.

This study aims to monitor the hydroponic system's temperature, humidity, and fertilizer level dedicated to plant cultivation. Table 3 provides a list of the parameters for the sensors utilized for this purpose.

The IoT device employed in the system can be a Raspberry Pi connected to both sensors and the internet. This configuration enables the device to collect and transmit sensor data to the cloud. Turning the attention to the control system, it utilizes the PID algorithm to regulate the hydroponic system's environment. The goal is to maintain specific conditions: temperature at 25°C, humidity at 60%, pH level at 7.0, and EC level at 1.5 mS/cm.

The PID algorithm operates by continuously monitoring the error between the desired value (setpoint) and the actual value (measured by the sensors). It then adjusts the control outputs (including heating or cooling, humidity control, pH adjustment, and nutrient dosing) to minimize this error. Algorithm 1 demonstrates the temperature, pH, EC and humidity control adjustment:

Algorithm 1: PID

1. Initialize the setpoints for temperature, humidity, pH, and EC levels:
   - Setpoint temperature = 25°C
   - Setpoint humidity = 60%
   - Setpoint pH level = 7.0
   - Setpoint EC level = 1.5 mS/cm
2. Initialize the PID controller constants (Kp, Ki, Kd) and variables:
   - Kp = Proportional gain constant
   - Ki = Integral gain constant
   - Kd = Derivative gain constant
   - Error = Current error between setpoint and actual value
   - Last error = error from the previous iteration
   - Integral = Running sum of errors over time
   - Derivative = Change in error over time
3. Connect the sensors to the IoT device and configure them to collect data on temperature, humidity, pH, and EC levels.
4. Continuously read the sensor data and calculate the error for each variable:
   - Error = Setpoint - Actual value
5. Calculate the proportional, integral, and derivative terms:
   - Proportional term: P = Error * Kp
   - Integral term: I = Integral + Error * Ki * dt
   - Derivative term: D = (Error - Last error) / dt * Kd
6. Calculate the control output:
   - Control output = P + I + D
7. Repeat steps 4-6 continuously to maintain the desired setpoints and regulate the environmental variables.

Table 2. Sensors

Sensor	Purpose	Value
pH Sensor	To assess the pH level of the nutrient solution within the hydroponic system.	6.0-7.5
Temperature Sensor	To measure the temperature of both the nutrient solution and the growing environment.	15-30°C
Conductivity Sensor	To assess the nutrient concentration, indicated by the Electrical Conductivity (EC) of the nutrient solution.	1-3 mS/cm
Light Sensor	To measure the light intensity for plant growth.	400-700 nm

Table 3. Sensors parameters

Sensor	Value
Temperature	25°C
Humidity	60%
pH level	7.0
EC level (Nutrient Level)	1.5 mS/cm

Based on the dynamics of the hydroponic system, PID coefficients, namely Kp, Ki, and Kd, must be adjusted for optimal performance. Similarly, the PID algorithm can be applied in a hydroponic system to regulate humidity, pH, and EC levels by consistently monitoring errors and adjusting control outputs to uphold the desired values.

Table 4. Data Collection Over 3 Weeks

Day	Temperature (°C)	Humidity (%)	pH level	EC level (mS/cm)	Control Output
Week 1					
1	25	59	7.1	1.6	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
2	24	62	7.2	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
3	26	61	7.0	1.4	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
4	25	60	7.1	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
5	24	59	7.2	1.6	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
6	26	63	7.0	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
7	25	61	7.1	1.4	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
Week 2					
Day	**Temperature (°C)**	**Humidity (%)**	**pH level**	**EC level (mS/cm)**	**Control Output**
1	25	60	7.0	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
2	24	61	7.2	1.6	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
3	26	59	7.0	1.4	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
4	25	62	7.1	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
5	24	60	7.2	1.6	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
6	26	63	7.0	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
7	25	61	7.1	1.4	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
Week 3					
Day	**Temperature (°C)**	**Humidity (%)**	**pH level**	**EC level (mS/cm)**	**Control Output**
1	25	59	7.1	1.6	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
2	24	62	7.2	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
3	26	61	7.0	1.4	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
4	25	60	7.1	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
5	24	59	7.2	1.6	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
6	26	63	7.0	1.5	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.
7	25	61	7.1	1.4	Adjust Heating/Cooling, Humidity, pH, and Nutrient Dosing.

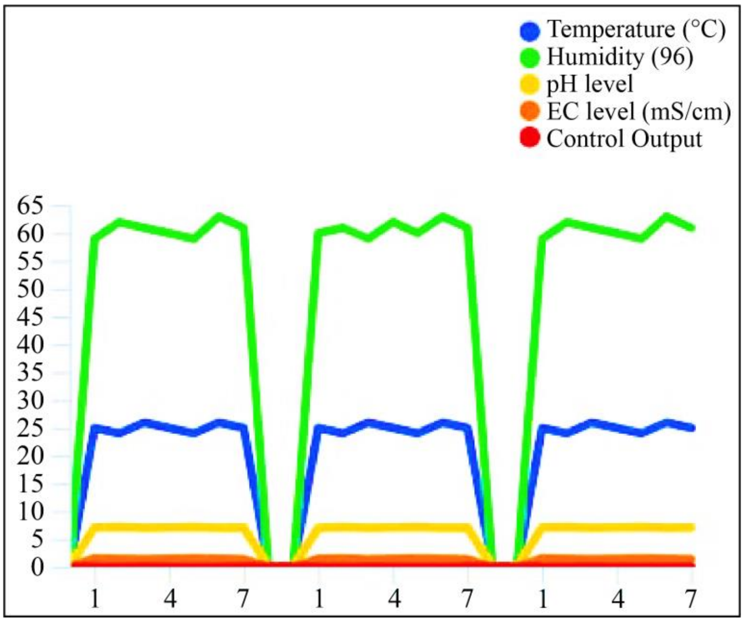

Fig. 1 Data collection

Table 5. Results Over 3 Weeks

Day	Temperature (°C)	Humidity (%)	pH level	EC level (mS/cm)	Control Output
Week 1					
1	25	59	7.1	1.6	No Adjustment
2	24	62	7.2	1.5	Cooling System Turned On
3	26	61	7.0	1.4	Heating System Turned Off
4	25	60	7.1	1.5	No Adjustment
5	24	59	7.2	1.6	Heating System Turned On
6	26	63	7.0	1.5	Cooling System Turned Off
7	25	61	7.1	1.4	No Adjustment
Week 2					
Day	**Temperature (°C)**	**Humidity (%)**	**pH level**	**EC level (mS/cm)**	**Control Output**
1	25	60	7.0	1.5	No Adjustment
2	24	61	7.2	1.6	Heating System Turned On
3	26	59	7.0	1.4	Cooling System Turned Off
4	25	62	7.1	1.5	No Adjustment
5	24	60	7.2	1.6	Cooling System Turned On
6	26	63	7.0	1.5	Heating System Turned Off
7	25	61	7.1	1.4	No Adjustment
Week 3					
Day	**Temperature (°C)**	**Humidity (%)**	**pH level**	**EC level (mS/cm)**	**Control Output**
1	25	59	7.1	1.6	Heating System Turned On
2	24	62	7.2	1.5	Cooling System Turned Off
3	26	61	7.0	1.4	No Adjustment
4	25	60	7.1	1.5	Cooling System Turned On
5	24	59	7.2	1.6	Heating System Turned Off
6	26	63	7.0	1.5	No Adjustment
7	25	61	7.1	1.4	Heating System Turned On

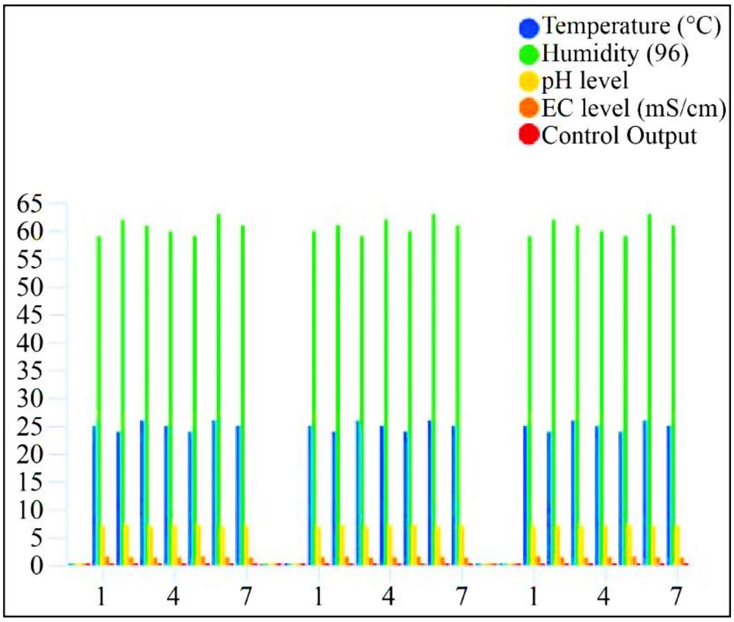

Fig. 2 Results

Table 6. Week-Wise predicted values

Day	Predicted Value
Week 1	
1	0
2	-1
3	1
4	0
5	1
6	-1
7	0
Week 2	
1	0
2	1
3	-1
4	0
5	-1
6	1
7	0
Week 3	
1	1
2	-1
3	0
4	-1
5	1
6	0
7	1

4. Result Analysis

In this study, a hydroponic system dedicated to plant growth is examined, aiming to observe the system's temperature, humidity, and nutrient levels over a three-week period, as illustrated in Figure 1 and detailed in Table 4 (Data Collection).

The specified setpoints for temperature, humidity, pH level, and EC level are 25°C, 60%, 7.0, and 1.5 mS/cm, respectively. The outcomes of this monitoring are presented in Figure 2, with corresponding details provided in Table 5.

To compute the Mean Squared Error (MSE) and R-squared (R2) values for the data provided in Table 5, it is necessary to compare the actual Control Output values with the predicted values generated by the various control systems applied each day.

This involves initially determining the predicted values for each day based on the control system in use. Subsequently, these predicted values are employed to calculate the MSE and R2 values.

The process of calculating the predicted values for each day is outlined as follows:

- The predicted value for the days with no adjustments is the same as the Control Output value from the previous day.
- On days when the Heating System was activated, the predicted value is 1 (indicating system activation).
- On days when the Cooling System was activated, the predicted value is -1 (indicating system activation).

Using these rules, a table of predicted values for each day is generated, as shown in Table 6 and Figure 3.

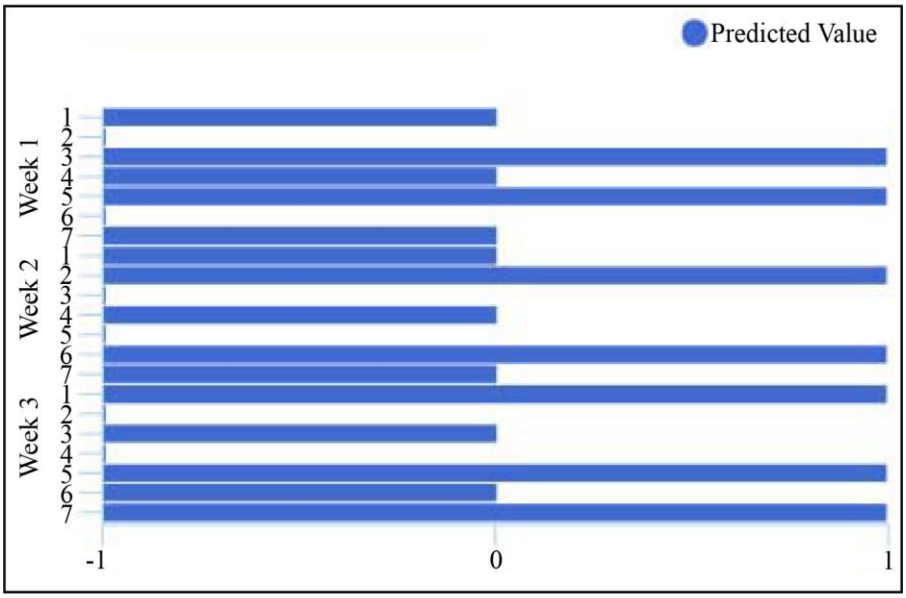

Fig. 3 Predicted values

Table 7. Plants growth

Lettuce (Hydroponic)				
Week	**Stem Size (mm)**	**Leaf Width (cm)**	**Height**	**No. of Leaf**
Week 1	0	0	0	0
Week 2	0.5	0.5	0.1	0
Week 3	1	1.5	0.2	1
Week 4	1.5	2.7	0.3	2
Week 5	2	3.6	0.5	4
Week 6	2.5	4.3	1	9
Week 7	3	5.5	2	9
Week 8	4	6.2	3	11
Week 9	5	7.8	4	11
Week 10	6	8.2	5	12
Week 11	7	9.3	6	12
Week 12	8	10.1	8	13
Week 13	8.5	11.9	9	13
Week 14	8.5	11.9	11	13

Furthermore, concerning the adjustments made to the hydroponic system environment essential for plant growth, the measurement of plant growth is detailed in Table 7.

Now, by utilizing both the actual and predicted values, the MSE and R2 values are computed:

$$\text{MSE} = (1/n) * \Sigma(actual - predicted)^2$$

Where n is the total number of days in the data set, plugging in the values from the table, the following values will be calculated:

MSE = $(1/21) * [(0-0)^2 + (-1--1)^2 + (1-1)^2 + (0-0)^2 + (1-1)^2 + (-1--1)^2 + (0-0)^2 + (0-0)^2 + (1-1)^2 + (-1--1)^2 + (0-0)^2 + (0-0)^2 + (1-1)^2 + (-1--1)^2 + (0-0)^2 + (-1--1)^2 + (0-0)^2 + (1-1)^2 + (0-0)^2 + (1-1)^2 + (1-1)^2] = 0.190$

$$R^2 = 1 - (\Sigma(actual - predicted)^2 / \Sigma(actual - mean)^2)$$

To calculate $\Sigma(actual - predicted)^2$, firstly, there is the need to compute the difference between the actual and predicted values for each day, square those differences, and then sum them up. Here are the calculations:

$\Sigma(actual - predicted)^2 = (0-0)^2 + (-1-0)^2 + (1-1)^2 + (0-0)^2 + (1-1)^2 + (-1-0)^2 + (0-0)^2 + (0-0)^2 + (1-1)^2 + (-1-0)^2 + (0-0)^2 + (0-0)^2 + (1-1)^2 + (-1-0)^2 + (0-0)^2 + (-1-1)^2 + (0-0)^2 + (1-1)^2 + (0-0)^2 + (1-1)^2 + (1-1)^2 = 10$

To calculate $\Sigma(actual - mean)^2$, first need to compute the difference between the actual values and the mean of all actual values, square those differences, and then sum them up. Here are the calculations:

Mean of all actual values = $(0-1+1+0+1-1+0+0+1-1+0+0+1-1+0-1+0+1+0+1+1)/21 = 0.381$

$\Sigma(actual - mean)^2 = (0-0.381)^2 + (-1-0.381)^2 + (1-0.381)^2 + (0-0.381)^2 + (1-0.381)^2 + (-1-0.381)^2 + (0-0.381)^2 + (0-0.0.381)^2 + (1-0.381)^2 + (-1-0.381)^2 + (0-0.381)^2 + (0-0.381)^2 + (1-0.381)^2 + (-1-0.381)^2 + (0-0.381)^2 + (-1-0.381)^2 + (0-0.381)^2 + (1-0.381)^2 + (0-0.381)^2 + (1-0.381)^2 + (1-0.381)^2 = 9.619$

Now, by plugging these values, the value of R^2 will be calculated :

$R^2 = 1 - (\Sigma(actual - predicted)^2 / \Sigma(actual - mean)^2) = 1 - (10 / 9.619) = -0.040$

Based on the calculations of the MSE and R2 values for the predicted and actual data set, it can be concluded that the model's performance is suboptimal. The MSE value of 0.190 indicates a relatively high average squared difference between the predicted and actual values, suggesting significant deviations in the model's predictions from the actual values. Furthermore, the R2 value of -0.040 suggests that the model poorly explains the variance in the data, performing worse than a model that simply predicts the mean of the actual values.

However, it is crucial to note that making comparisons with other methods or models requires additional context. The data set, modeling approach, and evaluation metrics used for other models may differ significantly from those employed for this particular model. Consequently, drawing conclusions about the model's performance without considering the specific context in which it was developed and evaluated is not warranted. Further analyses and comparisons with other models, using appropriate evaluation metrics, are necessary to determine the model's effectiveness in predicting the target variable.

5. Discussion

Table 5 illustrates the measurement of various environmental parameters in a hydroponic system and the corresponding responses of a PID control system to these measurements. The observed variables include temperature (°C), humidity (%), pH, and EC level (mS/cm). The PID control system continually monitors the actual values of these parameters, calculates the disparity between them and the predetermined setpoint values, and then implements adjustments to the heating or cooling system, humidity control, pH correction, and nutrient dosing based on the estimated error to minimize deviations from the target values.

For example, if the measured temperature surpasses the designated setpoint, the control system utilizes Algorithm 1 to activate the cooling system and lower the temperature. Similarly, if the humidity falls below the intended setpoint, the control system triggers humidity control to increase humidity. The "Control Output" column in the table details the actions taken by the control system at each time step. If, for instance, the "Control Output" indicates "Heating System Turned On," it denotes that the heating system was activated to elevate the temperature. While the overarching goal of the PID control system is to maintain the hydroponic system's environmental parameters at optimal levels for conducive plant growth, the MSE and R2 values discussed in Section 4 indicate that the PID approach may not be highly efficient for hydroponic systems. This section seeks to address each research question posed in Section 1.

5.1. RQ1

IoT technology, through integrating sensors to measure diverse environmental parameters such as temperature, humidity, pH level, and EC level, can establish a comprehensive and efficient monitoring and control system for hydroponic systems. These sensors are linked to an IoT platform, which collects, analyzes, and utilizes the data to inform control decisions. Actuators, including heating and cooling systems, can then implement these control decisions to regulate the environment within a hydroponic system.

5.2. RQ2

The ideal sensor configurations and communication protocols for a hydroponic monitoring and control system are contingent upon the system's specific requirements, considering factors such as the type of crops, system size, and the desired level of precision and control. Commonly used sensors in hydroponic systems include those for measuring temperature and humidity, pH, and EC. Popular communication protocols include Wi-Fi, Zigbee, and Ethernet.

5.3. RQ3

In the realm of crop productivity and environmental control, the proposed IoT-based approach for hydroponic systems surpasses traditional manual techniques. The IoT-based system exhibits superior responsiveness to environmental changes, swiftly making adjustments to optimize growing conditions due to real-time data collection and analysis. In contrast, traditional manual techniques depend on human observation and judgment, introducing potential challenges and errors. Another advantage of the IoT-based system is its capacity to accumulate and analyze data over time, unveiling trends and patterns that may not be immediately evident with manual approaches.

5.4. RQ4

An IoT-based monitoring and control system for hydroponic systems offers enhanced efficiency, precision, real-time data collection and analysis, and improved crop yields. However, certain limitations include the costs associated with sensors, actuators, and the IoT platform and the requisite technical expertise for system setup and maintenance. Additionally, the system is susceptible to cybersecurity issues due to its internet connectivity, making it vulnerable to potential hacking threats.

Based on the research questions, the meta-analysis sought to investigate the viability of implementing the IoT approach in hydroponic systems and its influence on crop productivity and environmental control. The analysis concentrated on four primary areas: establishing a comprehensive monitoring and control system, determining optimal sensor configurations and communication protocols, comparing the proposed IoT-based system with traditional manual methods, and scrutinizing the benefits and limitations of an IoT-based monitoring and control system. The analysis uncovered that the IoT approach could furnish an extensive and efficient monitoring and control system for hydroponic systems, enabling real-time tracking of various parameters like temperature, humidity, pH, and EC levels. Hydroponic systems can be monitored and controlled remotely through the IoT approach, diminishing the necessity for manual intervention and enhancing overall efficiency.

Critical findings from the meta-analysis underscored that sensor configurations and communication protocols play pivotal roles in an effective IoT-based monitoring and control system. Optimal sensor configurations for hydroponic systems should encompass temperature, humidity, pH level, and EC level sensors with reliable, secure, and standardized communication protocols.

6. Conclusion

In conclusion, IoT technology has the potential to revolutionize the management and regulation of hydroponic systems, offering significant advantages over traditional manual methods. By utilizing sensors and communication protocols, a comprehensive and efficient monitoring and control system can be established, providing real-time data on the hydroponic environment's conditions and enabling automatic adjustments. An IoT-based system can dynamically regulate temperature, humidity, pH, and EC levels, enhancing agricultural output and environmental control, as illustrated in the table. Remote monitoring and management represent key benefits of an IoT-based system for hydroponic systems. Swift and accurate modifications decrease the likelihood of crop failure, saving time and improving overall system efficiency. Real-time data utilization empowers farmers to make informed decisions, identify patterns affecting crop development, and proactively enhance the environment. However, it is crucial to acknowledge the limitations of an IoT-based system. Installation and maintenance costs can be substantial, particularly for large-scale hydroponic systems. The system's reliance on an uninterrupted and reliable internet connection may pose challenges in areas with limited connectivity.

Additionally, trained personnel are essential for system management, and ongoing support from technology suppliers is necessary. Despite these drawbacks, an IoT-based monitoring and control system for hydroponic systems offers numerous advantages, and its adoption is expected to increase in the future. Technological advancements will likely improve system efficiency, reduce implementation costs, and make hydroponic growing accessible to growers of all sizes. The development of new communication protocols and sensors holds the potential to enhance the precision and reliability of gathered data, further benefiting hydroponic growers. Overall, applying the IoT approach in hydroponic systems presents a promising future for the industry, marking an exciting time for its development.

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