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Original Article

Implementation and Development of a Novel Approach to Identify Sensor Data in Soilless Farming

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Abstract - *The rapid evolution of the technology provides a new environment to the agriculture sector to increase its production in a limited space and resources, such as human intervention, Soil, Water, and fertilizer, will increase the path of sustainability to make it climate resilient. For availing the above benefits, IoT and AI played a vital role; without them, thinking of soil-less indoor farming with low cost is very difficult. In this proposed experiment, one IoT infrastructure was developed and implemented in indoor farming successfully. In this study, Italian Basil was taken as a plant, and it was grown for thirty days and successfully harvested. Port optimization, Sensor calibration, Data error optimization, and IoT architecture setup with tiny edge server development have been carried out and tested in a physical experimental workable model. The findings of the proposed study are that without proper IoT implementation, establishing indoor farming is very challenging, and the growth rate of a plant in the platform is nearly a hundred percent, in comparison to soil growth, which is around seventy percent. In the explained work, only three input ports are used to read the data from six sensors, and each dataset is collected in the interval of two minutes, and all the platform sensor parameters are calibrated by taking standardized lab instruments. The platform may be very helpful for households and small farmers to achieve their sustainability and food security.*

Keywords - *Port Optimization, Sensor Calibration, Cost-Effective IoT Architecture, Climate Resilient Farming, Indoor Farming, Automated Agriculture Platform.*

1. Introduction

Agriculture is one of the core sectors in India because it offers primary livelihood means to most of the population, and it also supports government revenue through various taxes. The agriculture sector feeds the raw materials for many industries. Agriculture trade consists of about fifteen percent of India's total foreign exchange [1]. Earnings: The agriculture sector offers opportunities for employment, GDP, and food security in India. It provides forty-five percent of the total workforce and approximately eighteen percent of the country [2]. However, these advantages of agriculture intersect with the challenges posed by rapid urbanization, with metropolitan cities in India undergoing instantaneous urbanization due to better facilities of jobs, health care, and education. Major cities like Bangalore and Delhi have growth rates of 3.87% and 3.82% respectively [3] from 1991 to 2020. According to the projection, cities like Bangalore will achieve megacity status by 2030. However, this rapid urban growth also presents challenges such as environmental degradation, urban expansion, increasing demand for infrastructure and resources such as agricultural produce [4].

Agricultural food problems are usually a factor of improper agricultural practice that results in low yields and an overall reduction in food production. These are further worsened by soil degradation, lack of access to modern farming technologies, and climate change, therefore making farm profits increasingly difficult to maintain the food requirements of an increasing population [5]. Further, the degradation of the agricultural system leads to malnutrition because of the dependency on energy-dense but poor-nutrient foods [6]. Nutrition and obesity are the biggest burdens due to junk food, which is low in nutritional value but high in caloric content. It has thus been linked to a number of health risks, which include obesity, diabetes, and heart disease. The solution needs to come in the form of a change in eating healthy foods [7]. Additionally, another cause of degradation of agriculture is chemical-based fertilizers and pesticides. It has a number of demerits, such as soil, water, and air contamination, reduced biodiversity, and loss of organic matter in soil. These chemicals also have a negative impact on human health, such as respiratory problems, cancer, and neurological disorders [8]. To reduce the impact of chemical-based agriculture and to increase food security, emphasis is given on rooftop farming, which is a more sustainable, efficient, and cost-effective solution to meet the growing demand for food in urban areas.

The majority of rooftop farming is carried out using a soil-based method for growing plants. But soil-based farming on the rooftop also has various challenges like an increase in the load of the roof, unstable temperature, heavy rain, poor water drainage, labour-intensive and costly [9]. So, to scale up rooftop farming in urban areas, the better solution is the soilless agriculture process, which involves hydroponics, aeroponics, and aquaponics. These are efficient and minimize the waste. These are also easy to integrate with controlled environments like greenhouses and IoT [10].

Among the wide range of horticultural and leafy crops that are suitable for cultivation using hydroponic techniques, Basil is an excellent choice due to its inherent characteristics and the significant advantages that hydroponic cultivation offers. As a widely cultivated and highly popular culinary herb [11], there is high economic value and demand for Basil globally. Basil is easily adaptable to its surrounding environment and simple to grow [12], and it has a well-known capacity to flourish in various climates [13]. Hydroponics facilitates year-round, seasonally adjusted production, especially in regions with limited arable land or extreme environmental conditions that hinder conventional farming. These systems enable precise control over environmental parameters like temperature, pH, electrical conductivity, and nutrient solutions, leading to higher, more uniform yields and improved resource efficiency [14], with up to a ninety percent reduction in water consumption and reduced need for chemicals and pesticides compared to soil-based farming [15] using IoT. However, the crucial factor in using the IoT is the hardware implementation cost, as the microcontroller has a limited number of ports to receive data.

This study focuses on the design and implementation of an affordable IoT architecture by using port optimization to read data from multiple sensors in a single port. A hydroponic system is used with IoT, which enables precise monitoring over environmental parameters like temperature, pH, moisture, and TDS, leading to higher, more uniform yields and improved resource efficiency tailored for basil cultivation. The study aims to evaluate plant growth parameters, nutrient uptake, and overall yield under hydroponic conditions, with the goal of optimizing resource use and enhancing crop productivity. The current results are expected to complement the current body of knowledge that has been related to soil-free agricultural systems and also provide information that can be used to support the sustainable development of herbaceous crops in small-scale and commercial agricultural production. To implement all these things, the component cost is very high. When each component is analysed to optimize the cost, it is identified that the number of processors used is high because of the smaller number of ports to maintain the timing. However, agricultural operations are not time-bound; for this reason, the microcontroller or microprocessor can be attached to more sensors. Now the gap is here in how the extra sensors are connected to an existing microprocessor with a limited number of input and output ports.

1.1. Motivation and Contribution

To ensure food security for the rising population globally, agriculture needs a transformative approach, specifically in urban areas where conventional farming is not possible due to a lack of farmland. In precision agriculture, monitoring of inputs such as water, light, nutrients, and environment needs IoT, which enhances the growth and production. Small farmers and households desire a budget-friendly IoT setup for this.

This study contributes by implementing a novel setup of a reasonable IoT network by port optimization for the monitoring of farming without soil. In this research, a new algorithm is designed for this implementation, which may give a scalable solution for soilless farming. Additionally, generative AI is applied to predict the result from IoT data and plant images.

2. Literature Review

In the introduction section, the modern agricultural environment is becoming more and more connected to Internet-of-Things (IoT) technologies, which include smart sensors, autonomous vehicles, and data-centres in the form of cloud-based analytics platforms and data centres, supporting data-centres infrastructures. The academic literature defines several benefits of these systems, the most important of which is the effective utilization of water resources and the improvement in the process of making decisions in farming. Still, barriers to implementing technology are the high cost of sensors and monitoring equipment, demanding high initial capital that places an expensive burden on the smallholder farmers. Other limitations are that the technical knowledge of many growers is limited and that a strong broadband connection is required to adopt it, which only makes it more difficult. As a result, it is becoming increasingly agreed that urgent and collaborative steps between technology vendors, policymakers, and practitioners are imperative; this collaboration is considered the only possible way of attaining financial sustainability as well as operational feasibility of the IoT solution in the agriculture sector.

In today's era, studies have been focused on outlining the affordances and economic prospects of smart agriculture, which are based on advanced technology and challenges that are carefully recorded and documented. Although it can be appreciated that IoT has the potential of automating and optimizing a large number of processes in agriculture, the existing data indicate that the initial expenses on machinery are the heaviest problem, especially in developing economies.

Furthermore, the relatively high percentage of small enterprises does not have the financial strength to obtain equipment that is at least equal to or close to the standards used in different organizations, which has become a barrier to integration and an increase in the digital gap in the industry. The technical and operational aspects of the IoT implementation in the agricultural setting expect the implementation of modern sensor technologies that will bring the production outputs of the farming environment and will promote making automated decisions for agronomic purposes in the near future.

The financial aspect of obtaining and installing IoT-enabled sensors and additional equipment is one of the main scaling issues. The research outlines how these costs, such as purchasing hardware, installing it, providing power, and maintenance, may become prohibitive, especially for the massive operations or producers who are located in a rural setting. Recent agricultural innovations increasingly leverage remote sensing and machine learning for crop management, though field-based studies on basil biomass prediction remain scarce. One study addressed this by integrating multispectral data from both drones and satellites with machine learning algorithms to predict sweet basil fresh biomass in open-field conditions [19]. The latest Method of biomass estimation is not a destructive method, which provides useful data to meet crop management goals and to promote sustainability in the special type crop systems. But the validity of the developed models is not checked externally because the data obtained were calculated on a small number of research sites.

The development of hydroponic systems has increased recently because of a surge of popularity in the controlled environment type of agriculture. One study talks about an Internet of Things-based hydroponic system that has been specifically programmed to show the growth of medicinal crops like the Holy Basil, where Machine-Learning Algorithms will control the growth of the crop. The analysis of sensor data is carried out using Azure IoT Hub and Data bricks that make it possible to identify the optimal environmental conditions and shortage of nutrients [20]. This way of doing things aims at reducing human interference, improving the level of operational efficiency, and reducing the utilization of resources, hence promising to be an excellent direction towards indoor farming and sustainable production of medicinal herbs.

A systematic study on the growth parameters and productivity in the hydroponic and aquaponic floating raft systems was implemented to compare the sustainable basil cultivation practices. The analysis revealed the correlation of consecutive harvests. Even with the fact that the yield and photosynthetic capacity did not differ significantly between the systems, the aquaponic system yielded almost identical results of dry biomass and dry matter [21]. It is noted that harvest frequency had the greatest effect on the parameters of the plants, such as the distribution of dry matter and uptake of nutrients, and not the cultivation system. The most needed fact of information on the development patterns of Basil in controlled conditions, and gives the argument in favor of the care taken by aquaponics, as it is less dependent on chemical fertilizers.

Research was conducted to assess the effect of cultivation systems and working with micronutrient foliar sprays on photochemical properties, production, and growth of Basil. The comparative evaluation involved the treatments of open field, greenhouse soil, and hydroponic treatment, and the hydroponic systems failed to produce the best biomass and leaf nutrient ratios. In both cases of foliage being supplied with zinc or manganese in a regulated context, the promotion of compounds promoting health, phenolics, and flavonoids was always increased [22], regardless of the cultivation method applied. Accordingly, although open field agriculture is the most effective system in the production of bioactive constituents, hydroponic systems are the only systems that increase the ratio and the content of essential oils.

Studies have been carried out on the production of hydroponic Basil to determine the performance of different cultivars under different cultivation systems. Varieties of Basil were comparatively studied, and the Deep Flow Technology systems generated minimal growth of fresh weight as compared to the Nutrient Film Technology systems, but the cultivar finally dictated the yielding results. The production of fresh weight was different between basil types, such as Holy, Lemon, and Sweet Basil, with the purple Basil always recording the lowest biomass [23]. These results highlight the fact that the selection of cultivar, in the case where producers are focusing on the quality of the product to be produced, should be based on taste and harvest characteristics, and the selection of the hydroponic system, in the case where producers are focusing on the operational factors, should be based on the operations.

In response to global food security challenges, the integration of Internet of Things (IoT) with smart precision farming in soilless agriculture, encompassing hydroponics, aeroponics, and aquaponics, offers a sustainable solution. This approach leverages real-time monitoring and data-driven automation to optimize resource use, control environmental conditions, and achieve consistent crop production with reduced human intervention [24]. While hydroponics is often cited as the most efficient and profitable soilless Method, the overall benefits include addressing land scarcity, enabling urban and vertical farming, and ensuring year-round cultivation. Responding to the challenges of a shrinking agricultural workforce and the prevalence of basil diseases, a research initiative highlights the critical need for monitoring and management systems based on IoT for basil cultivation, integrated with machine learning. Current research on Basil often focuses on quality analysis rather than comprehensive growth monitoring and disease detection [25]. The proposed solution involves leveraging IoT to detect and analyze diseases in real-time, employing machine learning and deep learning for accurate diagnosis, thereby aiming to boost agricultural output, reduce labour costs, and enhance efficiency in basil farming.

Investigations into the nutritional value of Basil reveal that cultivation methods significantly influence its healthy compounds. One study specifically compared the nutraceutical properties and antioxidant activity of Basil grown in hydroponic versus soil environments, demonstrating that hydroponic cultivation notably enhanced both aqueous and lipid extract antioxidant capacities [26]. The research suggests that hydroponics offers advantages in reproducibility and precise control over nutrient delivery, which in turn contributes to elevating the plant's beneficial antioxidant content.

The major challenge is the preservation of quality and sustainability of fresh Basil before harvest, which has been mainly due to the vulnerability of the crop to cold damage and loss after harvest. An overall analysis determines the main factors that determine postharvest quality of Basil- nutrient management, irrigation, and light environment, as the major determinants of preharvest agricultural practice [27]. Nutrient regimes, such as the use of silicon or selenium, in combination with determining the level of irrigation, can minimize chilling damage and increase the concentration of antioxidants, extending the shelf life. Management of water is one of the pillars of the modern farming industry, which prompted the enrichment of innovative irrigation systems. The combination of machine learning algorithms with communication systems like LoRa and other wireless sensor networks can explain the example of an Internet of Things system that can help to introduce intelligent irrigation and water management of everlasting crops, including olive orchards (28).

These systems enable the immediate measurement of the environmental parameters, such as temperature and soil moisture, and further data analysis. They are not only used in the open fields, although they can also be applied in controlled settings, including greenhouses, where they are used in the production of soilless Basil. The key aim of these smart irrigation systems is to ensure the achievement of optimal water use by acting on the collected data to make decisions and automate, ensuring the water-related demands of current agriculture. To enhance production for basil growth and quality, setting the measurements is unavoidable in controlled environments. The effect of plant density, the strength of nutrient solution, and light intensity was tested with two varieties of sweet Basil that were cultivated using hydroponic conditions, which were Napoletano and Genovese. The findings showed that the increase in biomass and leaf count correlated positively with the increase in the size of leaves in Napoletano, and there was a correlation between the number of leaves and the advancement of the dry weight in Genovese (29). The research also found that higher planting densities, though reducing the individual plant biomass, did not result in a negative impact on the overall leaf area per plant, hence proving the nonlinear interaction of the cultivation parameters.

In order to constantly oversee facilities engaged in indoor cultivation, an efficient architecture uses low-cost, universal hardware, such as a combined micro-computer and a detached electronic prototyping foundation. The system monitors important plant growing conditions, which include light, temperature, PH, and gases. It should be noted that in a bid to achieve reliability and efficiency, it is designed with 2 specialized functions: one of backing up data (appearing as a parallel operation) to eliminate interruptions, and the other to balance the workload among the operating units. The design targets precision agriculture that will enhance quality crops. To confirm the identity of small transmitting devices, where typical encryption methods might not be practical due to device limitations.

The approach works by analyzing the unique physical characteristics, such as a fingerprint embedded in the device's radio transmissions. This involves transforming the digital signal data into an image using a visualization technique called a recurrence plot. This image is then analyzed by a Convolutional Neural Network for device identification. The technique achieved very high accuracy in testing compared to other identification methods based on statistics. Table 1 summarizes key factors that affect hydroponic growth, based on a broad review of the literature. The table compares each factor's effect, suggested range, and possible IoT monitoring, according to past research. This summary points out agreements in the literature and gives a reference for future experiments.

Table 1. Key factors that affect hydroponic growth

Sl.No.	Factor	Effect on Soilless Farming	Ideal Range for Plant Growth	Monitoring Method using IoT	References
1	pH	The most favorable pH in nutrient intake is very important. Strongly influences mineral absorption.	• General hydroponics: 5.5–6.5. • Sweet Basil (floating): 7.5.	In real time, the pH is monitored using an IoT sensor.	[21, 32, 20, 25, 26, 33, 27]

2	TDS / EC	Indicates nutrient concentration. • Low TDS = Deficiency. • High TDS = Harmful. • Requires frequent monitoring.	• Basil hydroponics: 1100µScm−1.	TDS is observed periodically using Sensors.	[11, 20, 25, 32, 33],
3	Water Temperature	Important for Plant health and avoiding hard water.	Hydroponicsbasil:22.5±0.5°C.	Water temperature is measured using sensors in real time.	[19, 20, 25, 32, 33]
4	Humidity	• High = fungal risk. • Low = wilting. • Optimal = better water balance.	• Basil(Genova):75% • Basil(Tigullio):65–70%.	DHT11 sensors measure humidity.	[20, 21, 25, 26, 32, 33, 34]
5	Air Temperature	Essential for plant growth and development.	• Sweet Basil (Tigullio): 24◦C.	Air temperature monitored using DHT11sensors.	[22, 25, 32, 33, 35]
6	Light Intensity	Enhances photosynthesis and plant growth.	• Holy Basil–16 hrs of full sunlight.	The LDR sensor is used to monitor the light for photosynthesis.	[20, 21, 25, 32, 33]
7	Moisture / Water Level	Appropriate water keeps photosynthesis, the plant's reproductive building block, and nutrient uptake process.	• Stable nutrient solution level.	IoT sensors remotely regulate moisture levels.	[21, 22, 25, 32, 33]

3. Hardware Setup

In the above paragraphs, all the parameters required for monitoring the agriculture are identified, and the optimised value for different parameters are identified. However, no other solution is found if the number of sensors is more than the processor's input and output ports. Then, what is the optimised way to interconnect the sensors in the platform. In the proposed study, one platform model is prepared in a practical experimental bed, and a larger number of sensors are connected than the input and output ports are used. A novel algorithm is also proposed for this developed model.

This model may grow leafy vegetables quickly using a small space suitable for an urban setup. In section 3, the hardware setup of the platform is explained, in section 3, its methodology is highlighted, section 4 deals with the result, and in section 5, the conclusion and the future work are described. In the above hardware setup, an optimized technique is used to connect more sensors using fewer hardware ports, and this setup is called a Relay-Based Multiplexer (RMUX), because a relay is used to connect multiple homogeneous sensors with a single port. In this setup, six sensors are used, of which four are digital, and two of them are analog. The relay is used as a switch that will switch on or off the sensor so that the data of multiple sensors can be read through a single analog or digital port. Two sensors are connected with one port, for instance, in this study, two digital sensors connected in one digital port and two analogue sensors connected using one analog port. The proposed technique can reduce the hardware cost of IoT architecture and can enhance the utilization of microcontroller units. The whole study is carried out using a water temperature sensor, a pH sensor, a TDS Sensor, a Light Sensor, a DHT11 to sense the ambient temperature, humidity, and moisture sensor, for the interconnection, three relays named as (R1, R2, R3), and input pin is connected with D5, D6, D7 ports of the controller. Each relay has one input pin, three output pins, and two supply pins. The input pin is helping to drive the relay, and the output pin acts as a switch. A relay acts as a single-pole, double-throw terminal, which means it has two states; this means one relay can control two sensors. DHT 11 and LDR sensor connected with the D1 port using R1 relay. Moisture sensor and water temperature sensor connected with the D2 port using R2 relay, and TDS sensor, and pH sensor connected with A0 port using R3 relay. In this study, six sensors connected with the controller using only three ports: D1, D2, and A0. Figure 1 explained the interconnection diagram in detail. In the next section, the working procedure of the interconnection diagram has been explained, and it has also tested in an Physical implementation mode to grow the plant in hydroponic system and read the data from the environment in a real time scenario, and make a comparison between the leafy veggies growth in soil, and the leafy veggies growth in a IoT based controlled environment.

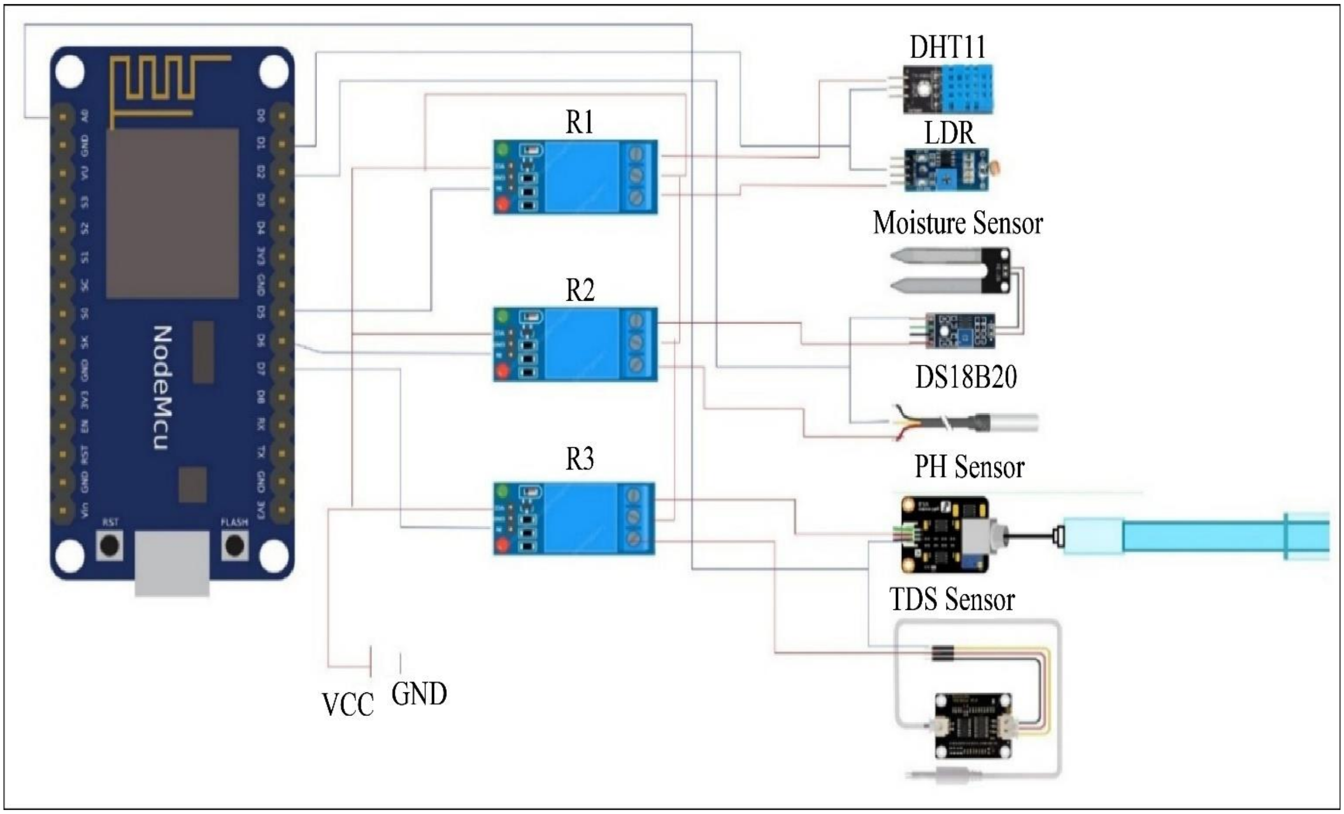

Fig. 1 Hardware integration diagram

4. Methodology

In the previous section, the details of the sensor interconnection architecture using RMUX have been explained. In this section, the functionality of the device achieved through the algorithm is explained.

The working algorithm is given below. Based on the algorithm1 when R1, R2, and R3 in 0 state pH Sensor, Water Temperature, and LDR sensor value can read using the port A0, D1, and D2 and when R1, R2, and R3 in a complement mode of the previous section pH Sensor, Water Temperature, and LDR sensor value can read, and it store into the database. Every one minute, the relay state is changed so that the system can switch to alternative sensors.

Using the above techniques, ports can be optimized, and the number of nodes in a network can be decreased, resulting in decreased network overhead. This hydroponics setup started from June 2025 in a small room located in Bhubaneswar (20°16’N, 85°47’E), Odisha, India. The weather at the time saw periods of both rain and sunshine, with daytime temperatures ranging between 29.25°C and 36 °C and relative humidity ranging from 75% to 86%. The experiment started in August 2025, inside a 24 square foot space equipped with an air conditioner to keep the environment stable. Basil seedlings were grown in a nursery for 20 days before being moved into the hydroponic system, where they were watched for 30 days. The hydroponic system was set up for indoor use, as shown in Figure 2. PVC channels were laid out horizontally.

Each channel had round holes for net pots, which held individual basil seedlings in a neutral growing medium. The channels were set at a slight angle so the nutrient solution could flow from the start to the end using gravity. A submersible pump in the nutrient tank below the channels constantly pushed the solution up to the start of the channels.

From there, it flowed over the plant root sand back into the tank. This design made sure the roots had a steady supply of both water and minerals while also getting enough air. A horticultural LED light strip, which mainly gave off red and blue light, was placed above the plants to help in photosynthesis. The light was kept on a regular schedule that was designed for basil growth.

Step 1: Start
Step 2: Set the D4, D5, and D7 pin as output pin
Step 3: Set the A0, D1, and D2 pin as input pin
Step 4: Initialize R1=0, R2=0, R3=0
Step 5: if R1=0 AND R2=0 AND R3 =0 then
    Read the LDR Sensor, Water Temperature, and pH Sensor value.
    Store into the database.

  End if

Step 6: Delay 2 seconds
Step7: R1 = R1 XOR 1
Step8: R2 = R2 XOR 1
Step9: R3 = R3 XOR 1
Step10: if R1=1 AND R2=1 AND R3=1then
    Read the TDS Sensor, DHT11, and Moisture Sensor value and store them in the database.

  End if

Step11:Sleep (1 Hour)
Step12:Goto Step 4
Step 13: End

Algorithm 1: Functionality of the device

Fig. 2 Hydroponic setup with basil plants

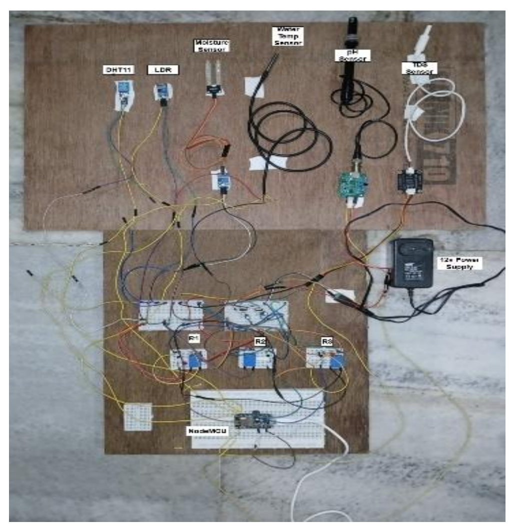

Fig. 3 Sensors Connected with NodeMCU

To keep track of the environment and nutrient levels, six sensors were used. The sensors were linked to a NodeMCU shown in Figure 3. A waterproof digital temperature sensor was put in the nutrient solution to monitor the root zone temperature, and a pH probe was placed in the channel to measure the acidity or alkalinity of the flowing water. A Total Dissolved Solids (TDS) sensor was used to measure the nutrient levels by reading electrical conductivity and turning those readings into parts per million.

A DHT sensor above the plants recorded air temperature and relative humidity. An LDR sensor module is used to measure light intensity in a room. A soil moisture sensor was used for comparison, allowing the reading strobe to be compared between dry and wet conditions. The NodeMCU was programmed using the Arduino Integrated Development Environment in C++ to gather data in a specific order at set times. Each set of data included water temperature, pH, TDS, air temperature, relative humidity, and light intensity. The recorded data was sent to a laptop through a WiFi connection and saved in a database. The database showed both current readings and a history of readings with timestamps. Before the experiment, all sensors were calibrated to make sure they were accurate.

The pH probe was first put in a standard buffer solution of pH 4.0 for two minutes, rinsed with distilled water, and then put in a pH 7.0 solution. To work with the system, the probe was calibrated against three standard buffer solutions at pH 4.0, 7.0, and 10.0. The calibration curve was then uploaded to the program to correct for any offset automatically. The TDS sensor was calibrated using two reference solutions, including a 342 ppm NaCl standard solution and a commercially available, calibrated solution from a different brand. Adjustments were made to the conversion factors to match actual ppm values.

The water temperature sensor was checked against a certified glass thermometer in a controlled water bath, using both ice water and heated water for calibration at multiple points. The DHT environmental sensor was compared with a calibrated digital hygrometer, and its accuracy was checked at both room and controlled temperatures. The soil moisture sensor was calibrated by testing it in dry soil, wet soil, and water. The light sensor returns 0 when light is on and gives 1 in the off condition.

To check that the data was reliable, manual readings were taken regularly using handheld tools like a pH meter, EC meter, digital thermometer, and hygrometer. These readings showed that the system based on IoT consistently gave values within an acceptable range of error. Regular maintenance was also done throughout the study, including cleaning the pH probe and TDS electrode to prevent the buildup of nutrient deposits. The nutrient solution for the experiment was made using distilled water and a commercially available hydroponic nutrient mix designed for leafy greens. Before being used in the system, the solution was adjusted to the optimal levels for basil growth, with the pH kept between 5.5 and 6.5 and the TDS levels set to the recommended values. The submersible pump ran constantly to keep the solution circulating, and the tank was refilled daily with distilled water to make up for water lost due to evaporation and plant use. This Method reduced changes in nutrient concentration and ensured the root-zone conditions stayed consistent throughout the experiment.

5. Result

The newly implemented architecture is functioning optimally on the hydroponics system, by which multiple homogeneous sensors can be connected in one port. This architecture reduced the cost of hardware setup in agriculture. The execution time of the novel algorithm is O(n), where n is the number of sensors, and it can be split into n/2, and can read n/2 sensor data at a time.

Let
Z = clock frequency of microcontroller in Hz.

t number of sensors.

rt response time of sensors in seconds.

c number of clock cycles needed to read and process one sensor.

tm = maximum allowed time to complete all sensor readings.

Time required for one sensor = $rt + \frac{c}{z}$

Total time for t sensors

$$t \times \left(rt + \frac{c}{z} \right)$$

In time-bound condition, Total time $\leq tm$

$$t \times (rt + \frac{c}{z}) \leq tm$$

So the maximum sensors supported is = $\frac{tm}{rt+\frac{c}{z}}$

For example, if a microcontroller clock is 16 MHz, response time is 0.005 seconds, clock cycle required is 8000, and maximum allowed time is 0.1 seconds, then the maximum number of sensors supported is 100/5.5=18.18. It supports up to 18 sensors only. In case of non-bounded time, it supports up to the total number of GPIO pins available, and in this work, the number of GPIO pins increases through the RMUX, and it supports up to 256 sensors.

Fig. 4 Plants on Different Days

Fig. 5 Soil-Grown and Hydroponic Plant

Over the thirty days of observations, the progress of a plant was observed physically, and all the parameters shown in Figure 4 were measured. At the start, it was a young seedling, small in size, with just a few leaves present. As time passed, a slight increase occurred in the dimensions of its current leaves.

New, small leaves were possibly emerging from its central point. By the middle of the observation period, the plant's growth was very clear. The existing leaves had noticeably gotten bigger, resulting in a fuller canopy. This development went forward, with leaves evolving to be larger and stronger, giving the plant a thicker look overall.

At the end of the thirty days, the plant was in a healthy state. Its leaves were not only large but also well-formed, which signalled a clear increase in size from the first view. These changes show a steady and healthy development pattern during the period under review. All the data recorded from the developed platform using this architecture-based experimental device is provided to the generative AI.

Correlation analysis was used to define the interactions between different environmental determinants in the hydroponic system. The positive correlation close to +1 means that two variables are likely to change in the same direction at the same time; for example, when the temperature in the room and the humidity have a positive correlation, a rise in temperature would be linked with a rise in humidity. A high negative correlation (close to -1), on the other hand indicates that with the increase in one variable, the other variable decreases and therefore the variables are in an inverse relation like the one that could be between pH and nutrient concentration (total dissolved solids, TDS) where a higher concentration of TSS value may be associated with a lower pH. Correlations that are close to zero mean a weak or non-existent linear association, meaning such variables as Light Intensity (LDR) and water temperature could vary independently of one another.

All these interrelationships enable the determination of parameters that affect other ones and those that do not affect each other in the hydroponic environment. Analyses of time-series measurements of hydroponic sensor data gathered during the period between the end of July and the beginning of September 2025 show that the environmental factors were stable and did not pose a threat to the plants.

Consistency in water temperature was found in the range of 25.0 degrees Celsius to 25.8 degrees Celsius, which indicated efficient thermal control, and changes in pH were situated at 5.6 to 6.4, implying regular nutrient changes.

Total Dissolved Solids (TDS) were moderately set at between 900 and 1150 ppm, indicating routine changes in nutrients. The results indicate that the experimental platform is working perfectly.

Humidity showed more variation from 54 to 72 percent, respectively, which could be due to environmental control cycles. On the whole, both readings led to the conclusion that the hydroponic environment was properly preserved and monitored under the conditions of the controlled environment, as they contribute to the natural plant growth.

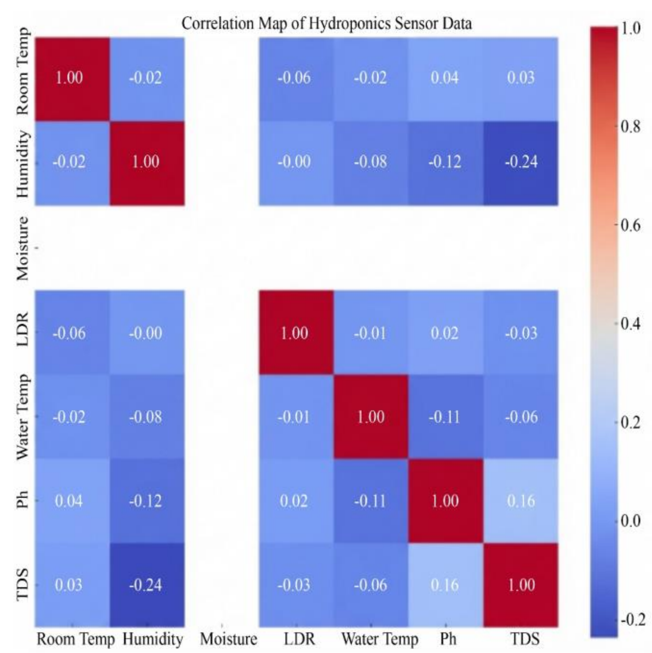

Fig. 6 Co-Relation of IoT Data

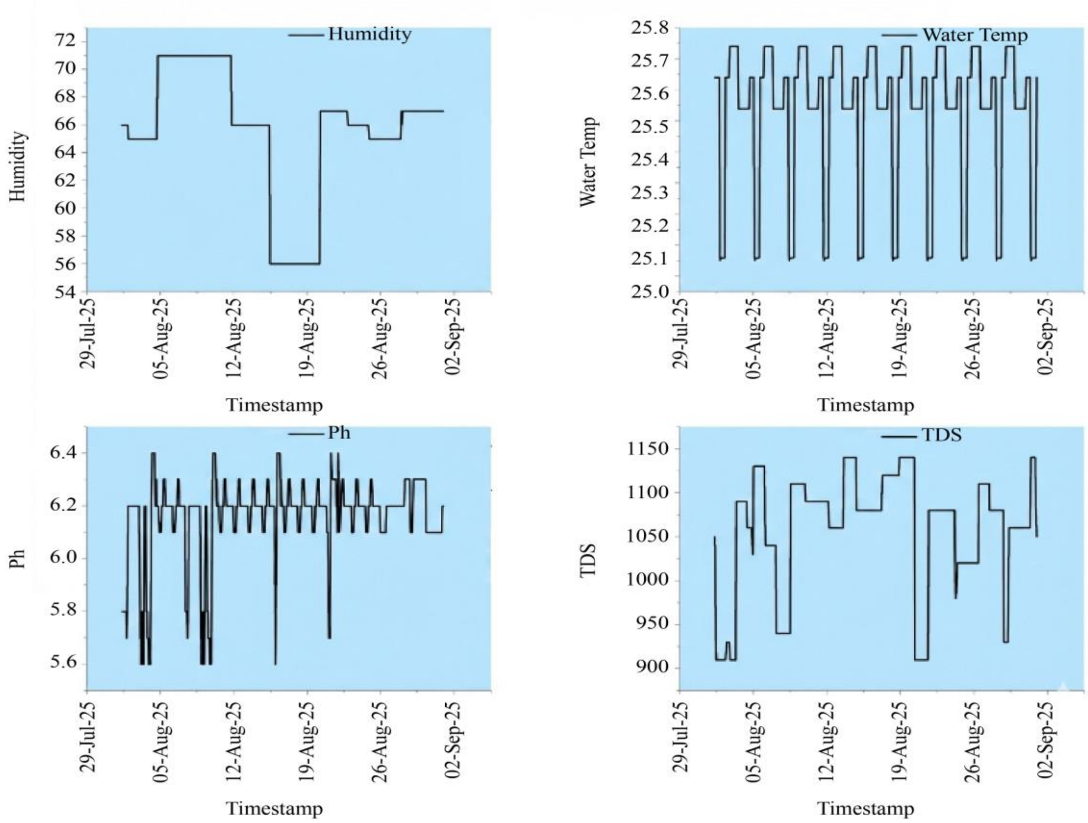

Fig. 7 Graph of different parameters

Table 2. Is a Comparative analysis of the RMUX approach proposed in relation to the traditional sensing architectures

Reference No	Objective	Architecture	Port Properties	Sensor Used	Expansion of Architecture
36	Design a low-cost sensor network using low-cost processors and Microcontrollers	Traditional. It is using the dedicated port	It is Fixed	Temperature, moisture, PH, EC, Luminosity, electro-valves, pumps, lamps	Difficult
37	Multi-sensor acquisition using minimal Arduino pins	Arduino and passive resistor/diode networks	It is semi-dynamic	Temperature, gas, LDR, humidity, switches	Possible but limited by ADC resolution and noise
38	To design a cost-effective air quality monitoring system using Arduino.	Arduino used with MQ sensors, ESP-01, and ThingSpeak	Fixed	MQ135, MQ7, DHT11	Possible but limited by power and ADC pins
39	Microcontroller-based sensing system for collecting data from multiple sensors in a compact and cost-effective manner.	Sensors connect to dedicated pins, are processed by Arduino, and produce output.	Fixed	Temperature, humidity, light/proximity	Limited by I/O pins
Proposed Work	Design a low-cost sensor network by expanding its I/O port using RMUX with the Existing Architecture.	It is used on a dedicated port as well as an expanded port	It is Dynamic	All types of Analogue and digital sensors can be used. The I/O port supported the range of 0 to 5 volts.	Easy for Expansion

6. Conclusion and Future Work

The agriculture sector is rapidly evolving with technology, which leads to future food security and sustainability. In this paper, the RMUX architecture was successfully implemented in a hydroponics system, and this can enlarge the use of IoT in farming. The data and images collected are uploaded for observation by a generic AI, and interpretation is made that the plants in the hydroponic system are growing with precise decisions to improve yield, save resources, and reduce cost using the IoT monitoring system. In subsequent studies, this architecture is extended for edge-to-edge communication, and an M2M protocol will be designed for this architecture. This architecture is also used to automate the nutrition supply to the plant when needed. It can also be used to automate the water flow, which reduces the energy consumption of the system.

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