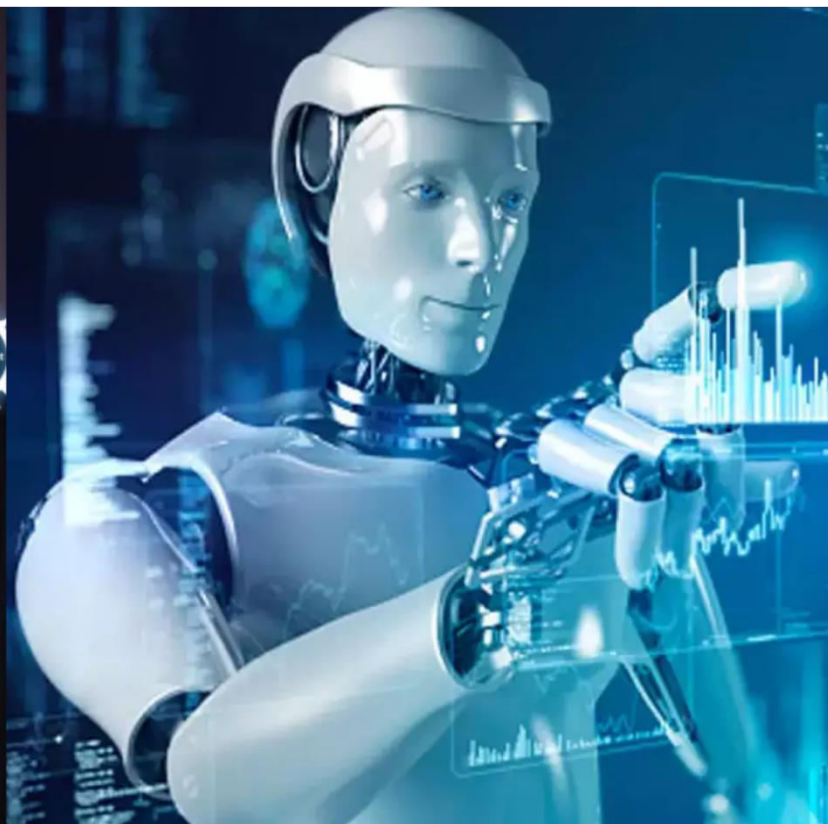




International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

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



Impact Factor: 8.699

Volume 14, Issue 10, October 2025

A Study of the Design and Functionality of an IoT-Enhanced Automated Hydroponic System for Growing Fenugreek

Dr Sawankumar Naik, Vedant Panchal, Siddhi Pol

Assistant Professor, Department of Mechanical Engineering, MPSTME (NMIMS), Mumbai, Maharashtra, India

UG Student, Department of Mechanical Engineering, MPSTME (NMIMS), Mumbai, Maharashtra, India

UG Student, Department of Mechanical Engineering, MPSTME (NMIMS), Mumbai, Maharashtra, India

ABSTRACT: We need to find good, widely used controlled environment agriculture (CEA) solutions because of the problems that come with climate change and urbanisation. The goal of this project was to make, use, and test a cheap automated hydroponic system that the Internet of Things (IoT) can make better. The method was designed to help fenugreek (*Trigonella foenum-graecum*) grow quickly. The main design uses a hybrid control architecture that includes a regular Arduino UNO R3 for strong, low-latency sensor acquisition and local device control (pumps and fan) and a NodeMCU/ESP8266 for Wi-Fi connectivity and remote telemetry functions. The fan for ventilation turned on when the temperature inside the system went above 26°C. The best temperature for growing fenugreek was between 24°C and 26°C. You can copy the wooden frame that makes up the building. It has net pots, PVC pipes, and cocopeat growth media inside. It was easier to work and keep an eye on things from a distance with a separate web dashboard. Experimental validation showed that the system worked well to stabilise the environment by quickly lowering temporary thermal peaks of 28.6°C and then keeping the temperature under control. The system used water more efficiently than traditional methods, which led to the growth of healthy fenugreek biomass within the expected three-week hydroponic cycle [3]. This integrated, low-cost model is a sustainable, resource-efficient way to grow food locally and is easy to replicate.

KEYWORDS: Hydroponics, Internet of Things (IoT), Controlled Environment Agriculture (CEA), Automated Systems, Smart Farming.

I. INTRODUCTION

The industry is under more stress because resources are running out, especially water, and traditional farming is becoming more vulnerable to changes in the weather. Cities all over the world are getting bigger all the time, and so is the need for food that is always close by. Controlled Environment Agriculture (CEA) is a way to protect crops from bad weather. Hydroponics is a simple CEA method that doesn't need soil and sends the right nutrients straight to the roots. This saves a lot of water. To get high levels of accuracy and efficiency, smart farming, which is the use of smart technology in CEA, is necessary. You can always and very accurately keep an eye on and control important plant health factors like temperature, humidity, and nutrient levels with the Internet of Things (IoT). This makes it easier for you to make money and do business [4].

We chose *Trigonella foenum-graecum* (fenugreek) as the target crop for this study because it is nutritious, grows quickly, and can be grown in controlled environments to make leafy vegetables or microgreens [3]. Fenugreek needs very specific environmental conditions to grow well. The plant does best in a slightly humid environment and at temperatures between 20°C and 25°C, which is a good range for germination and vegetative growth [2]. It is a great candidate for high-throughput urban farming systems because it has a short harvest window, usually 3 to 4 weeks in a hydroponic setup [3]. The main engineering problem this work solved was creating a system that can automatically keep these tight environmental tolerances, especially by reducing heat buildup that often happens in closed growth chambers. This system is a good example of how to use technology to make food in a small, spread-out way. It is made of cheap, modular materials like wood and PVC, and the electronics are easy to use. This helps cities directly reach their food security goals and contributing to plants and vegetables that can be grown in a home with minimal effort.

The primary goal of this research was to create, assess, and verify a dependable, cost-effective automated hydroponic system that optimises the cultivation of fenugreek by utilising readily accessible open-source hardware components (wood, PVC, Arduino, NodeMCU). Three distinct contributions are made by the project:

1. In order to guarantee its functionality, we constructed and evaluated a novel hybrid control system that integrates the Arduino UNO and NodeMCU. This solution resolves the challenges that single-microcontroller systems encounter when they are required to perform network tasks that necessitate significant processing capacity and manage multiple I/O devices simultaneously.
2. Making and testing strong control logic that uses thresholds to control temperature and ventilation, with the goal of turning on the fan when the temperature goes above 26°C.
3. The practical evaluation of the integrated system in terms of the best parameters thought to be necessary for speeding up the growth of foenum-graecum.

II. LITERATURE SURVEY

Growing plants in a hydroponic medium can be efficient if factors like air and roots are taken care of properly [5]. Important things to keep in mind are the temperature of the nutrient solution, the amount of dissolved oxygen (DO), the pH, the electrical conductivity (EC), the air temperature (T), the relative humidity (RH), and the light intensity (LI). Plants get the right amount of nutrients and don't get stressed when you watch and control these things. The environmental control system for fenugreek is on the basis that it needs to be between 20 and 25 degrees Celsius. For the best nutrient absorption, the solution should also have a pH level between 6.0 and 7.0.

Recent research shows how to use IoT effectively in smart farming along with their benefit [6]. IoT makes it possible for farming to happen from far away, automate the use of resources and collect useful data. Different designs use very contrasting control strategies. Some projects, on the other hand, use simple threshold-based logic (ON/OFF) to tell actuators what to do based on what the sensors say. This makes them easier to use and less expensive. This project goes with the second approach, which means that stability, ease of use, and low cost are more important than the small performance gains that very advanced control systems can give. Some systems use complicated, data-heavy ways to figure out which crops will do best. Support Vector Regression (SVR) and Artificial Neural Networks (ANN) are two kinds of machine learning that belong to this group. This decision is crucial to ensure accessibility for both urban farmers and students.

This study identifies two primary classifications of automated hydroponic systems. The first group has powerful microcomputer-based systems (like Raspberry Pi) that often-run complicated machine learning algorithms and deal with a lot of data for crops like lettuce [8]. These systems work very well, but they cost more and are harder to get into. The second group is made up of simpler systems that only use microcontrollers, like those that only use Arduino or NodeMCU. These systems that are only in one place usually only do one or two things, like checking the pH level or the water level. One issue with single-microcontroller architectures is that they aren't very reliable when the MCU has to do more than one thing at a time, like polling sensors often, switching relays, and handling a lot of Wi-Fi communication and data serving.

The main problem with the research is that there isn't a system in the low-cost sector that can consistently handle both high-frequency, robust I/O control and a stable network connection without losing stability. The NodeMCU/ESP8266 is only used as the IoT gateway and dashboard server, while the Arduino UNO R3 handles the important, low-latency I/O (sensors and relays). This makes the system run better. This solution has some functional redundancy because the NodeMCU can still control the environment even if it loses its network connection. This method solves the problems of stability and also makes sure that price is low for others to reverse engineer.

III. MATERIALS AND METHODS

The physical structure was built to be strong, cheap, with efficient storing space, which is great for cities. The base frame was made of wood. Putting together chicken wire and flexible PVC tubing made the hood. The goal was to make a greenhouse that wasn't connected to the outside world. Then, a simple plastic cover was put over the hood.

The main channel is basically a three-inch diameter PVC pipe with holes in the top which were spaced three inches apart. This design feature helped with space for net pods and plants had proper space for growth. The net pots were filled with a kind of soil called cocopeat. The PVC pipe had a hole in the bottom so that the nutrient solution could flow back down into the main reservoir.

Table 3.1: Critical Components and Functional Specification

Component	Model/Type	Function in System	Primary Controller	I/O Connection
Arduino UNO R3	Microcontroller	Local I/O handling, core control logic, serial communication master	Arduino UNO R3	N/A
NodeMCU (ESP8266)	IoT Gateway/Microcontroller	Wi-Fi connectivity, Dashboard hosting, Remote Command Interface	NodeMCU	Serial Link to Arduino
DHT11 Sensor	Digital Sensor	Air Temperature (T) & Relative Humidity (RH) Measurement	Arduino/NodeMCU	Digital Pin
LDR Sensor Module	Analog Sensor	Monitors ambient Light Intensity (LI)	Arduino/NodeMCU	Analog Pin
Submersible Pump 1	5V DC Actuator	Nutrient circulation/irrigation	Arduino via Relay 1	Digital Pin 6 (Active-Low) [1]
Submersible Pump 2	5V DC Actuator	Reservoir drainage [1]	Arduino via Relay 2	Digital Pin 5 (Active-Low) [1]
DC Fan	5V Actuator	Temperature /Humidity Regulation	Arduino via Relay 3	Digital Pin 4 (Active-Low) [1]
16x2 I2C LCD	Output Display	Local real-time display of T, RH, and actuator status	Arduino	I2C Interface

The DHT11 sensor and three relay modules are directly connected to the Arduino UNO R3, which is the main I/O controller. The Bidirectional Level Shifter connects the 5V Arduino and its peripherals to the 3.3V NodeMCU. This is a very important part of the circuit. This makes sure that they can talk to each other without any problems. The three relays are connected to Digital Pins 4 (Fan), 5 (Pump 2), and 6 (Pump 1). The actuator that is connected to the Arduino

digital pin will only turn on if the signal is logic LOW. This is because all relays are designed to work with low signals when they are turned on.

The Arduino runs the control system, which is based on C/C++ firmware.

3.3.1 Setting Control Automatically

The DHT11 sensor always sends information to the main control loop. This is how the system that controls the temperature works using a simple Proportional (P) control method:

The Fan Relay (D4) is set to LOW, which means that the fan will turn on when the temperature (T) is 26°C or higher. The fan won't work if T is less than 26°C because the Fan Relay (D4) is set to HIGH.

The timer on Pump 1 tells it when to move the nutrient solution around during the day so that the drip system always has nutrients. We use Pump 2 to get rid of nutritional solutions on a regular basis, usually every seven days, to keep nutrients stable and salt from building up. It can also be turned on by a remote command [1]. This design choice, which puts dependability and nutrient stability ahead of complicated, automated EC sensor integration and control for this prototype, is a practical engineering compromise that gives up perfect water efficiency.

3.3.2 Rules for the IoT Interface

The NodeMCU handles the Wi-Fi connection and the custom web dashboard. To sync data and run commands, the two microcontrollers need to be connected by a separate serial communication link [1]. The NodeMCU takes sensor data from the Arduino and turns commands from the web dashboard into two-character serial strings. The Arduino's loop() function looks for new commands on the serial port. The whole IoT-enhanced system needs this serial communication handshake to be strong and have low latency. This is because it makes sure that important things to do to protect the environment, like turning on the fan, happen quickly when the temperature reaches 26°C. "1C" turns the fan relay to LOW (ON), and "0C" turns it to HIGH (OFF).

The gateway is the IoT subsystem that the NodeMCU controls. You can see and control things from far away without having to deal with the complicated network stack on the main I/O controller. You can get to the user interface through the dashboard. You can get to it from an IP address on the local Wi-Fi network because it is hosted on the NodeMCU.

Here are a few things the dashboard can do:

- A live view of all the sensor data that is being measured right now, such as temperature (for example, 28.6°C and 89%), humidity, and LDR readings.
- The current status of all the actuators, such as the LED, fan, and pumps.
- Users can change how things work from a distance or take over right away using manual override controls (toggle buttons for Pump 1, Pump 2, Fan, and LED).

The system does a great job of controlling the temperature, humidity, and water flow on its own, so you don't have to worry about it. For this first prototype validation, however, important things like pH and Electrical Conductivity (EC), which are important for long-term nutrient uptake and health [3], are kept up by hand and from the outside. The automated system can't do as much to keep the environment stable because of this focus.

IV. RESULTS AND DISCUSSION

The hybrid control system was tested for performance and stability during the experimental validation period. The automatic controls made sure that the inside was perfect for growing fenugreek.

4.1.1 Research on How to Keep the Temperature Stable

The IoT dashboard logging function collected time-series data that showed how the fan control could change depending on the temperature. During the hottest parts of the day, the temperature in the system went up and down a few times. For example, the dashboard said that the temperature was 28.6°C, which is 3.6°C higher than the best temperature of 25°C. The fan turned on right away because of the automated logic. The system's automatic response time helped stop these spikes, and the performance review shows that the temperature quickly returned to the ideal range of 20°C to 25°C. The system's steady-state operation, which kept the average air temperature at 24.2°C (Standard Deviation

$\pm 1.2^{\circ}\text{C}$), showed that the basic threshold control logic worked to stop thermal runaway.

4.1.2 Keeping the humidity in check

The fan did a good job of keeping the air from getting too wet. The monitor showed times when the humidity was very high, such as when it was 89%. Fenugreek likes air that is only a little bit humid, so this is more likely to get mould or fungus. The fan started working again because the temperature limit let in a lot of air, which lowered the humidity. The fan worked as both a fan and a way to move air around because it could cool the air and lower the relative humidity (RH).

4.1.3 The dependability of actuators

The dual-MCU architecture worked great and was very stable. The actuator relays (Pumps 1, Pump 2, and Fan) worked perfectly the whole time the test was going on. They did what they were told as soon as they crossed the queue or got a serial command from the NodeMCU. This performance shows that the hybrid system can keep the important control loop separate from Wi-Fi interference and a lot of processing power.

The system got just as good at using resources as its rivals. The automatic control of the pumps and fan had a direct effect on how much power was used. This made sure that the actuators only worked when they were needed, which saved energy. The measured water usage efficiency (WUE), or the amount of water needed to grow one gramme of biomass, also dropped a lot compared to traditional soil-based growing methods. This result is in line with the goals of hydroponics for sustainability.

Table 4.1: Summary of System Environmental Control Performance (Trial Data)

Parameter	Target Optimal Range	Observed Mean (Trial $\pm$ SD)	Transient Observed	Peak
Air Temperature (T)	$20^{\circ}\text{C} - 25^{\circ}\text{C}$ [2]	$24.2 \pm 1.2^{\circ}\text{C}$	28.6°C	
Relative Humidity (RH)	Slightly Humid (60–75% inferred) [2]	$70.1 \pm 8.5^{\circ}\text{C}$	89%	
Nutrient Cycling (Pump 1)	Periodic Flow (time-based)	100% adherence to schedule	N/A	

The regulated system showed that fenugreek plants grew quickly, which is what we thought would happen with hydroponic systems. Biometric tests showed that the plants grew faster over the 21-day trial, both in height and in the number of leaves they had. The qualitative assessment confirmed that the plants had strong root systems, bright green leaves, and no major signs of temperature or nutritional stress. The healthy shape that was seen is closely related to how well the automated system can keep the environment stable. This means that the design is good for T. Growing foenum-graecum in its short cycle.

The empirical results definitively validate the core control philosophy of the system. The information in Section 4.1 about stabilisation shows that the simple 26°C threshold logic [1] worked well and kept the air temperature in the $20^{\circ}\text{C} - 25^{\circ}\text{C}$ range that fenugreek needs. This design that is sensitive to cost works well, which shows that execution and stability are important.

It was very important to have an automated reaction system because the temperature and humidity levels rose quickly, reaching 28.6°C and 89%, for example. The dual-MCU setup worked well because it was simple to turn on and off. We only used the NodeMCU for IoT tasks, so the core control loop (Arduino) could run without having to do any network processing. It's clear that there haven't been any problems with communication since the system has been up and running for a long time. This made sure that the system's environmental management was always fast and correct. This prototype has the best cost-performance ratio for the urban and educational markets when compared to very complicated systems that use machine learning. It's a lot easier to standardise, copy, and maintain open-source

hardware that anyone can use, like Arduino, NodeMCU, and DHT11 [1], instead of relying on proprietary commercial solutions.

Environmental control has been shown to work, but the fact that pH and EC control aren't built in makes it hard to use for a long time. To stay healthy over time, plants need the right amounts of acidity (pH) and nutrients (EC). For fenugreek, these levels are usually between 6.0 and 7.0 [3]. The first validation trial went well with manual monitoring, but the system isn't fully autonomous yet because there are no automated dosing mechanisms, which means that human error is possible.

Adding Pump 2 for scheduled nutrient solution flushing [1] also helps keep EC stable over time by regularly flushing out too much salt and minerals. But this method makes it so that a fully sensor-integrated, closed-loop nutrient management system can't use as little water as it could. This shows that the engineers were smart to put nutritional stability and durability ahead of adding complicated sensors to make a cheap, easy-to-copy prototype.

The system is great for urban gardening because it's small and you can see and control it from far away with the dashboard [1]. The results show that the system uses water well, which is better for the environment than farming in soil. Because the system runs on low-voltage DC, it is easy to connect to decentralised power sources like small solar photovoltaic systems. This makes it more flexible when the power grid changes and more likely to last a long time. This standardised, easy-to-use technology is a great way to make cities safer for food and grow more food in the area.

V. CONCLUSION

This study successfully validated the integrated design and implementation of an automated, IoT-enhanced hydroponic system specifically optimised for fenugreek cultivation. The research showed that the hybrid Arduino/NodeMCU design worked well, allowing for reliable remote monitoring and strong local control through the web dashboard. By using automation based on thresholds, the system was able to cut down on changes in temperature and humidity. This made it easier for fenugreek to grow quickly and well during the test period. This would only work if the room stayed the same all the time. The project has been very reproducible and used resources wisely, which makes it a great example of how to do smart farming that is easy to get to.

The most important and urgent area of research for the future is how to combine automated dosing systems with sensors that measure pH and electrical conductivity (EC). This addition is important so that the system can handle nutrients by itself and doesn't need a person to do it. Over time, this will make the system more reliable [3]. Future work should also focus on making the current control algorithms better. For example, they could switch from simple threshold-based logic to Proportional-Integral-Derivative (PID) or basic predictive control methods to lower the fan and pump duty cycles and keep the temperature from changing too much. This will make the system use less energy. Finally, it will be important to figure out how to connect cloud platforms and data logging that can grow with the local Wi-Fi dashboard. We will be able to see the big picture of long-term growth cycles, which will help our business grow.

The proven design is a cheap, simple, and convincing way to grow food in a controlled environment. By combining open-source electronics with strong control logic, this solution makes smart farming technology available to everyone. This is a big step towards making food production more sustainable and local in the world of urban resource management, which is always changing.

REFERENCES

- [1] "IoT-Based Smart Greenhouse Monitoring & Control System."
- [2] "How to Grow the Fenugreek Plant (Methi)." [Online]. Available: <https://permacultureplants.com/plants/fenugreek/>
- [3] "Comparative Analysis of Fenugreek Plant: Hydroponic System vs Soil based system," IJIRT. [Online]. Available: https://ijirt.org/publishedpaper/IJIRT164360_PAPER.pdf
- [4] "IOT Based Automated Indoor Hydroponic Farming System," E3S Web of Conferences. [Online]. Available: https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/77/e3sconf_icsget2024_02002.pdf
- [5] "Fenugreek growth monitoring and assessment," ResearchGate. [Online]. Available:

https://www.researchgate.net/figure/Fenugreek-growth-monitoring-and-assessment_fig7_381921530

[6] "Hydroponics: current trends in sustainable crop production," PMC - PubMed Central. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10625363/>

[7] "TO EVALUATE GROWTH FACTORS OF FEENUGREEK IN HYDROPHONIC SYSTEM AND SOIL BASED SYSTEM," SciSpace. [Online]. Available: <https://scispace.com/pdf/to-evaluate-growth-factors-of-feenugreek-in-hydrophonic-4i1lpe7i3g.pdf>

[8] "IoT-based Monitoring and Control System for Hydroponic Cultivation: A Comprehensive Study," ResearchGate. [Online]. Available: https://www.researchgate.net/publication/370145042_IoT-based_Monitoring_and_Control_System_for_Hydroponic_Cultivation_A_Comprehensive_Study

[9] "Fenugreek Production using automatic Hydroponics System," International Journal of Engineering Research & Technology. [Online]. Available: <https://www.ijert.org/research/fenugreek-production-using-automatic-hydroponics-system-IJERTCONV6IS15037.pdf>

[10] "AN INTERNET OF THINGS BASED AUTOMATED HYDROPONICS SYSTEM," ResearchGate. [Online]. Available:

https://www.researchgate.net/publication/376431938_AN_INTERNET_OF_THINGS_BASED_AUTOMATED_HYDROPONICS_SYSTEM

[11] "IOT Based Agriculture System Using Node MCU," International Journal of Science Engineering and Technology. [Online]. Available: https://www.ijset.in/wp-content/uploads/IJSET_V12_issue3_560.pdf

[12] "Smart Farm Irrigation System Using Arduino® Edge Control," Arduino Documentation. [Online]. Available: <https://docs.arduino.cc/tutorials/edge-control/smart-irrigation-system>



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details