

Development of Smart Fertigation System for Chili Plantation in Greenhouse Environment

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Abstract

This report presents the development and evaluation of a smart fertigation system tailored for chili plantation within a greenhouse environment, aimed at optimizing soil moisture levels to enhance agricultural efficiency. The system employs a NodeMCU ESP8266 development board to interface with a Blynk server, enabling real-time monitoring and control through a smartphone application. Key components include capacitive soil moisture sensors, a DHT22 temperature and humidity sensor, an L298N motor driver, and a 12V DC water pump. The system utilizes both Bang-Bang and Proportional Integral Derivative (PID) controllers to regulate irrigation based on precise soil moisture measurements. Through trial and error, the optimal PID parameters were determined as $K_p = 7.2$, $K_i = 4$, and $K_d = 1$, achieving a steady-state error of 1.24% and a rise time of 5.4 seconds. When the soil moisture level drops below 50%, the system automatically activates the irrigation pump and sends a notification to the user's smartphone. The integration of IoT technology with traditional irrigation methods demonstrates significant improvements in maintaining soil moisture, thereby promoting faster plant growth and reducing the risk of overwatering. This abstract summarizes the methodology, hardware and software implementations, and the performance outcomes of the smart fertigation system based on extensive testing and data analysis.

1. Introduction

In the realm of contemporary agriculture, sustainable and technologically advanced practices are paramount to address challenges like climate change and resource constraints. Greenhouses, which offer regulated conditions for optimal plant growth, stand as a significant innovation in agriculture. This study focuses on developing an intelligent fertigation system tailored for greenhouse-based chili (*Capsicum annum*) cultivation. Chili peppers are an essential agricultural crop with nutritional, economic, and medicinal benefits [1]. Malaysia, being the world's fifth-largest pepper grower, has a substantial demand for chili peppers, with domestic consumption at 55,420 tonnes annually while domestic production only meets 24,428 tonnes [2]. The shortfall necessitates substantial imports, highlighting the critical need for increased domestic production, particularly during peak periods like religious holidays.

Furthermore, greenhouse-based agriculture has emerged as a viable solution to the limitations of traditional farming, offering controlled environments that mitigate the impacts of adverse weather conditions and seasonal variability [3]. Greenhouses provide the ability to regulate temperature, humidity, light, and other critical factors,

creating ideal conditions for plant growth. These temperature control, humidity management, and light modulation, are crucial for optimizing the growth conditions for chili peppers [4]. This controlled environment is particularly beneficial for high-value crops such as chili peppers (*Capsicum annuum*), which have specific cultivation requirements [5]. Fertigation, the combined application of fertilizers and irrigation, plays a pivotal role in modern agricultural practices. The efficiency of drip irrigation is underscored by its ability to achieve field-level application efficiencies of 70–90%, significantly higher than traditional surface irrigation methods. This higher efficiency results from reduced losses due to surface runoff and deep percolation, making drip irrigation increasingly popular, especially in water-stressed regions [6]. This method not only improves crop yield and quality but also reduces labor and resource wastage, making it an integral component of precision agriculture.

Despite the advantages of fertigation and greenhouse technology, the manual management of irrigation and fertilization remains labor-intensive and prone to human error [7]. Inconsistent application rates and timing can lead to nutrient imbalances, affecting plant health and productivity [8]. Furthermore, traditional monitoring methods for soil moisture, temperature, and humidity are inadequate for providing real-time data necessary for optimal decision-making. This underscores the need for an automated system that can continuously monitor and adjust these parameters to maintain ideal growing conditions [9]. In order to build the smart fertigation system, IoT is needed. Nowadays, various IoT-based solutions have been proposed and implemented in recent years [10]. IoT enables the collection of real-time data from various sensors, facilitating informed decision-making and automated control systems [11]. Also, IoT-based technologies have revolutionized modern agriculture by enabling real-time monitoring and control of various environmental parameters. The integration of IoT with agricultural practices enhances resource efficiency and productivity, making it a critical component of smart agriculture.

In this research, the primary focus is on developing and implementing an intelligent fertigation system tailored for greenhouse-based chili cultivation. Central to this endeavor is the accurate monitoring and management of soil moisture levels. Soil moisture measurements are pivotal not only in mitigating soil erosion and land degradation but also in enhancing crop yields, especially in semi-arid environments where low soil moisture content adversely affects agricultural productivity. Maintaining optimal soil moisture levels through precise fertigation scheduling is critical for maximizing chili pepper yield and quality within controlled greenhouse conditions [12]. This study aims to leverage IoT technologies to automate soil moisture monitoring and fertigation processes, thereby improving resource efficiency and crop productivity in chili cultivation.

Lastly, the objective of this research is to design and develop a smart fertigation system for chili cultivation in a greenhouse environment. Then, study different control schemes suitable for a smart fertigation system and evaluate the effectiveness of the selected control scheme on chili growth.

2. System Architecture and Implementation

This chapter delves into the methodology employed throughout the research and development of the smart fertigation system designed specifically for chili plantation within a controlled greenhouse environment. The initial phase of this study involved conducting a comprehensive literature review, which focused on sensors, water pumps, and methodologies pertinent to system development. The aim was to identify, analyze, and assimilate existing approaches, thereby establishing a solid foundation for the subsequent phases of the study. The systematic approach utilized in the design, testing, and evaluation of the smart fertigation system is elucidated in detail, offering transparency into the research process. The following sections present a structured framework for the development of the system, encompassing hardware and software implementation, IoT platform integration, experimental setup, data collection procedures, and analysis methodologies. Each step is designed to ensure the reliability, efficiency, and functionality of the smart fertigation system in optimizing irrigation management for enhanced chili cultivation outcomes.

2.1 System Architecture

The smart fertigation system is designed with a robust system architecture that integrates various sensors and actuators with the NodeMCU ESP8266 development board, ensuring efficient monitoring and control of soil moisture levels. The central processing unit, NodeMCU ESP8266, handles data collection from the capacitive soil moisture sensor v1.2, which measures soil moisture levels and sends analog data to the ESP8266. Additionally, the DHT22 sensor provides digital readings of temperature and humidity, crucial for environmental monitoring

and optimizing irrigation schedules. The L298N motor driver interfaces with the ESP8266 to control the 12V DC water pump, allowing for the implementation of PID or PWM control to regulate water flow accurately. The 12V DC water pump, operated by the motor driver, delivers water to the soil based on the detected moisture levels. The Blynk IoT platform facilitates remote monitoring and control through a user-friendly interface on mobile and desktop devices, displaying real-time data from the sensors and allowing users to control the irrigation system remotely. This system architecture ensures seamless integration of all components, maintaining optimal soil moisture levels and enhancing water use efficiency and crop health.

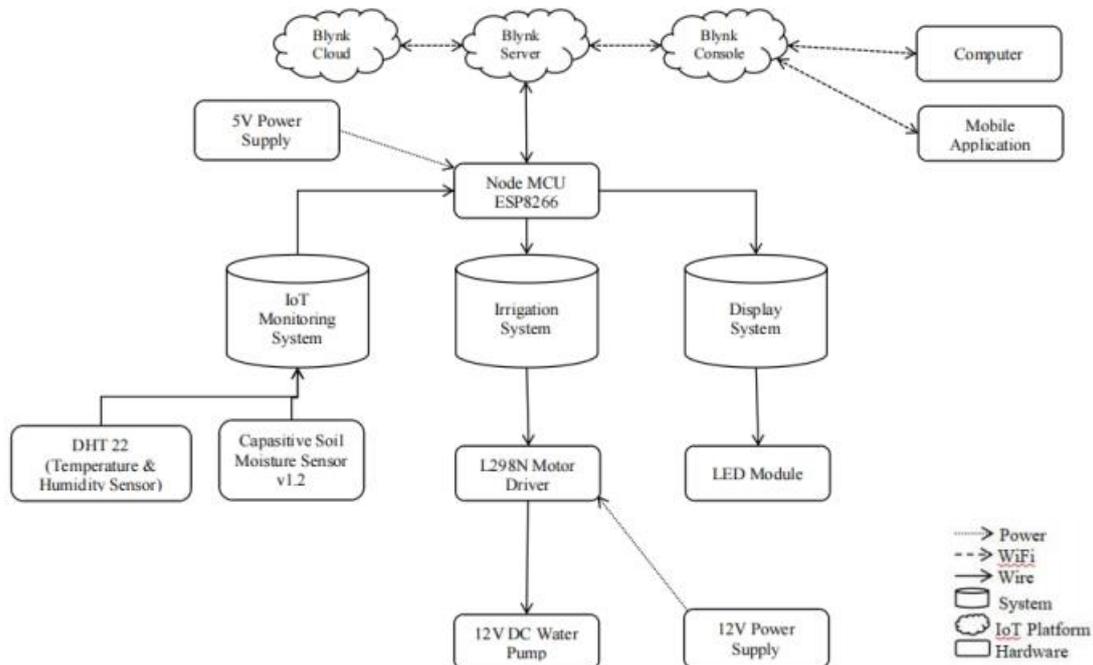


Fig. 1 Block Diagram of Smart Fertigation System

2.2 Hardware Selection

The development of the smart fertigation system required careful selection of hardware components to ensure efficient operation and integration. The NodeMCU ESP8266 was chosen over the Arduino development board primarily due to its built-in Wi-Fi functionality, which is essential for IoT applications. The ESP8266 enables seamless wireless communication and remote monitoring capabilities, making it highly suitable for this project.

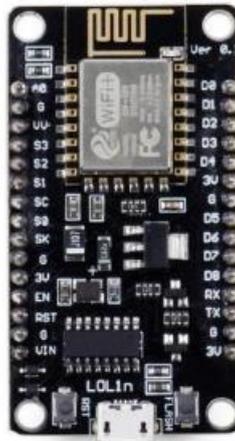


Fig. 2 NodeMCU Lua V3 ESP8266 WIFI with CH340C

For soil moisture measurement, the capacitive soil moisture Sensor v1.2 was selected instead of the resistive soil moisture sensor. The capacitive sensor offers better accuracy and longevity as it is less susceptible to corrosion, providing more reliable moisture level readings crucial for precise irrigation control. The experiment done by

Adla et al. showed that the capacitive soil moisture sensors are more accurate than the resistive soil moisture sensors (Adla et al., 2020) [13]. Figure 2 shows the accuracy of capacitive soil moisture sensors (SMEC300 and SM100) and resistive soil moisture sensors (YL69 and YL100), in 4 different soils. The closer the bubble is to its origin, the more accurate the sensor is. As a result, capacitive sensors can provide a more precise assessment of the soil's state for effective plant monitoring.

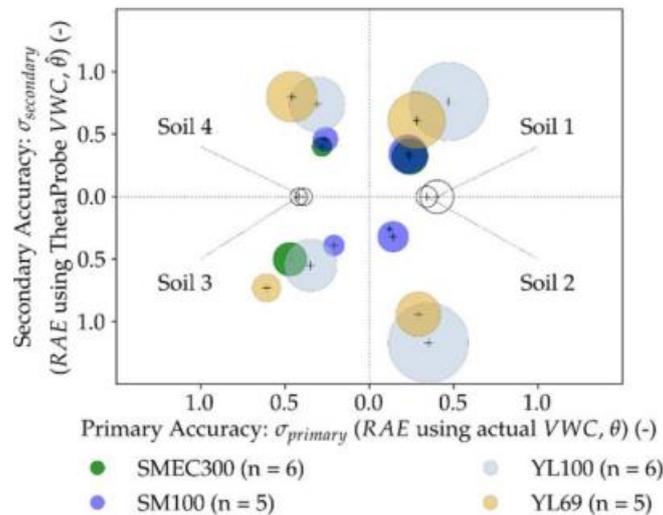


Fig.3 Accuracy of Capacitive Soil Moisture Sensors (SMEC300 and SM100) and Resistive Soil Moisture Sensor (YL69 and YL100) (Adla et al., 2020)

Temperature and humidity monitoring were handled by the DHT22 sensor, which was preferred over the DHT11 due to its improved accuracy and wider range for both parameters. This selection ensures more precise environmental monitoring, which is critical for optimizing irrigation schedules. To control the water pump, the L298N Motor Driver was chosen for its ability to implement PID or PWM control on the motor, allowing fine control over the water pump's operation. This ensures efficient water delivery based on the control algorithms implemented in the system. A 12V DC water pump was selected for its compatibility with the system's power requirements and its capacity to deliver sufficient water flow for irrigation purposes.

2.3 IoT Platform Selection

The IoT platform selected for this project was Blynk, due to its user-friendly interface and robust features. Blynk allows for easy integration with the ESP8266, providing seamless remote monitoring and control of the smart fertigation system. The platform supports real-time data visualization, alerts, and notifications, enhancing the system's functionality and user experience. By leveraging these carefully selected hardware components and the Blynk IoT platform, the smart fertigation system is capable of optimizing soil moisture levels effectively, thereby improving water use efficiency and crop health.



Fig. 4 Application of Blynk in Smart Agriculture

2.4 Flowchart of Smart Fertigation System

This section details the working principles underlying the smart fertigation system, explaining how the various components interact to ensure effective and efficient irrigation management.

The system follows a structured flowchart to monitor soil moisture levels and control irrigation effectively. Initially, the system is powered on and connects to the Blynk server, indicated by a yellow LED. The NodeMCU ESP8266 then reads analog input from the capacitive soil moisture sensor and digital inputs from the DHT22 sensor to obtain temperature and humidity data. The raw soil moisture level is transformed into a mapped value ranging from 0 to 100. Based on the mapped soil moisture level, the system makes decisions regarding irrigation. If the soil moisture level is between 0 and 50, a notification is sent to the user's smartphone indicating low moisture levels, and the water pump is activated by setting the corresponding virtual pin (V3) to 1. The green LED is turned on, and the red LED is turned off to indicate the pump is running. Conversely, if the soil moisture level is between 50 and 100, the water pump is turned off by setting the virtual pin (V3) to 0, and the red LED is activated while the green LED is deactivated to indicate the pump is off.

The system continuously sends and displays soil moisture levels, water pump voltage supply, temperature, and humidity on the Blynk interface, with data stored on the Blynk cloud and daily reports sent to the user's email. The process repeats at regular intervals with a delay of 0.01 seconds between readings, ensuring real-time monitoring and control. This structured flowchart ensures the smart fertigation system operates efficiently, maintaining optimal soil moisture levels through automated irrigation while providing real-time data and control capabilities to the user.

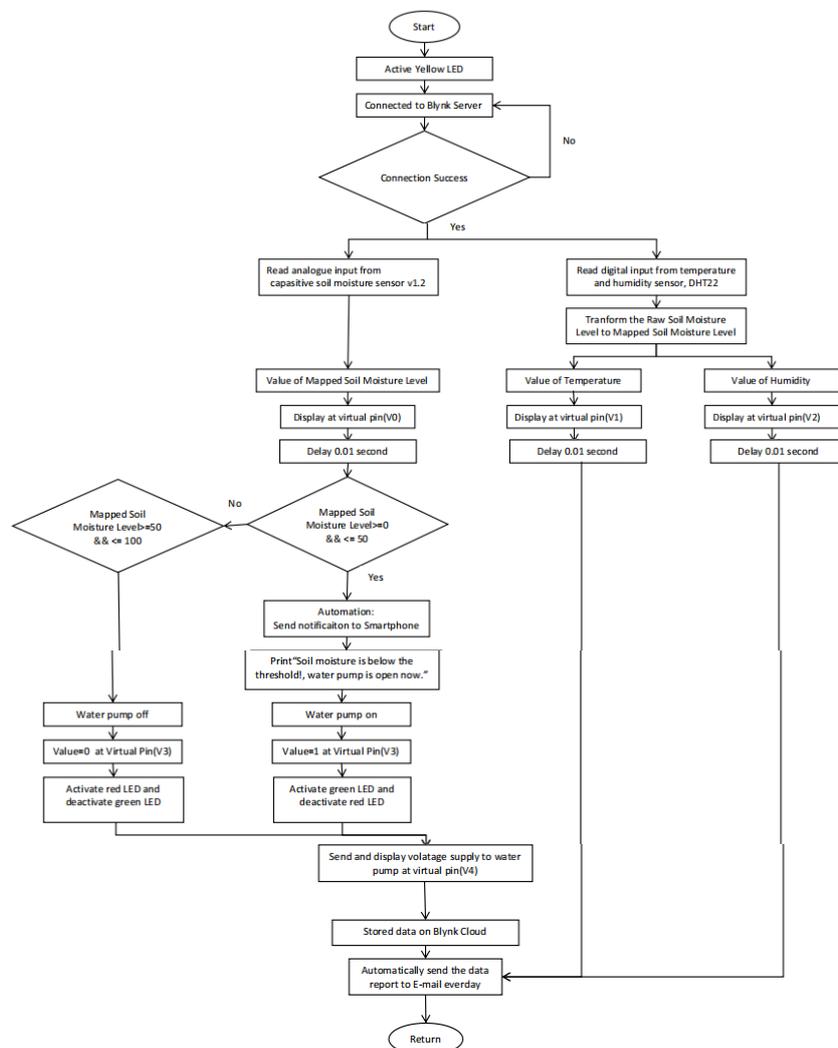


Fig. 5 Flowchart of Smart Fertigation System

2.5 Hardware Implementation

In this section, the practical steps taken to implement the hardware for the smart fertigation system are discussed. Figure 6(a) shown the electrical schematic diagram of the smart fertigation which drawn using Fritzing. It provides a detailed illustration of the wiring and connections between various components, such as the NodeMCU ESP8266, capacitive soil moisture sensor, DHT22 sensor, L298N motor driver, and 12V DC water pump. This diagram served as a blueprint for assembling the system, ensuring all connections were made correctly and safely. Following the schematic, a physical prototype was constructed, as shown in Figure 6(b). This prototype encapsulates the integration of all hardware components, demonstrating the feasibility and functionality of the designed system in a real-world application. The careful attention to the schematic during assembly ensured that the prototype accurately reflected the planned design, allowing for effective testing and validation of the system's performance.

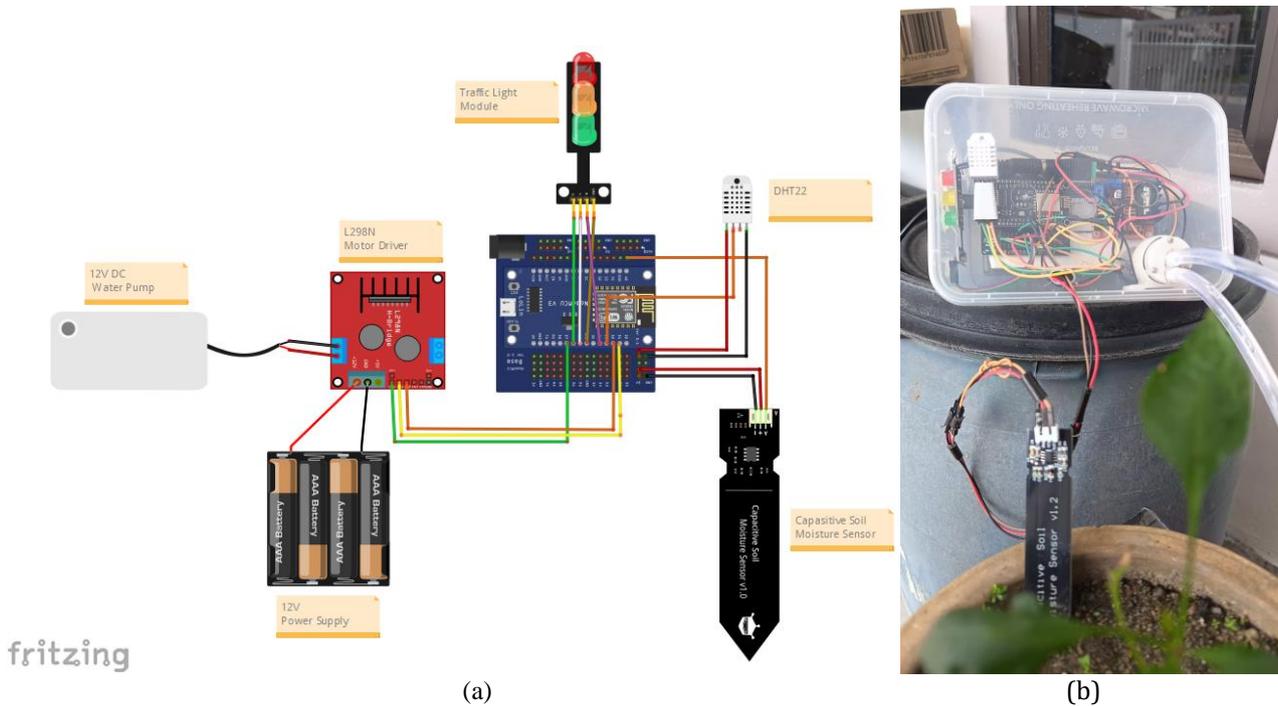


Fig. 6 (a) Electrical Schematic Diagram for Smart Fertigation System (b) System Prototype

2.6 Software Implementation

The Blynk software's interface includes various widgets such as gauges, labels, sliders, and custom charts to display real-time data to users. Virtual pins are utilized to manage data transmission between the sensors and the Blynk application, ensuring smooth interaction and control. Figure 7(a) illustrates the computer dashboard and Figure 7(b) shows the smartphone dashboard of smart fertigation system, both configured using Blynk's intuitive interface. These dashboards utilize various widgets such as gauges, labels, sliders, and custom charts to display real-time data from the system's sensors. Virtual pins (V0-V4) are employed to facilitate seamless data transmission between the NodeMCU ESP8266 microcontroller and the Blynk application, enabling efficient monitoring and control functionalities. Virtual Pin V0 is dedicated to displaying soil moisture levels, V1 for temperature readings, V2 for humidity measurements, V3 for controlling the water pump (ON/OFF), and V4 for adjusting the water pump voltage. This structured layout ensures that users can easily monitor crucial environmental parameters and control irrigation operations in real-time.

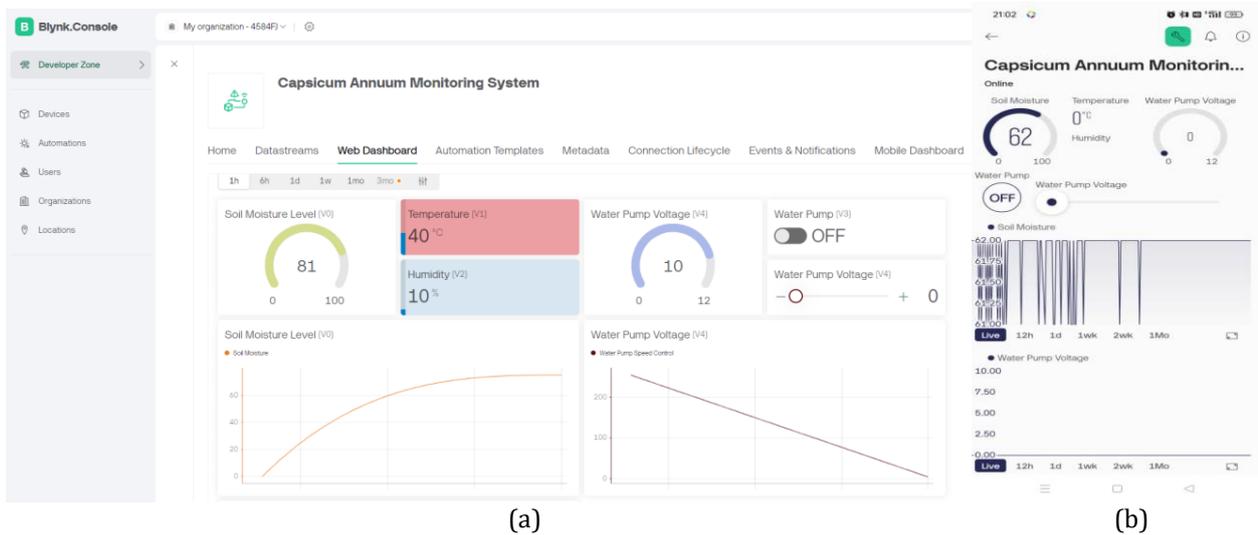


Fig. 7 (a) Computer Dashboard (b) Smartphone Dashboard

Additionally, the system also features an automatic notification function that alerts the user via smartphone when the soil moisture level falls below a predefined setpoint, ensuring timely irrigation actions.

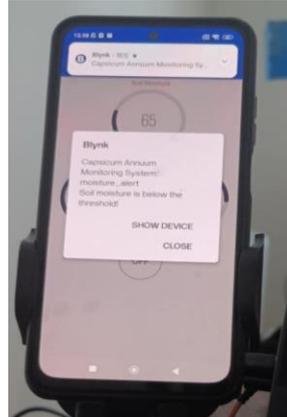


Fig. 8 Smartphone Notification from Blynk when Soil Moisture Drop below Setpoint

3. Results and Discussion

This chapter presents the results and discussion based on the system's performance and data analysis. The hardware and software implementations are evaluated, demonstrating how the system's components work together to optimize soil moisture levels. Temperature and humidity data were analyzed, comparing indoor and outdoor environments to understand their impact on soil moisture. The Bang-Bang controller's performance is discussed, noting its simplicity and effectiveness despite some overshoot and water wastage issues. The PID controller's superior performance is highlighted, showcasing its ability to maintain optimal soil moisture levels with minimal overshoot and zero steady-state error. The analysis provides insights into the system's efficiency and potential areas for improvement, such as enhancing sensor calibration and exploring sustainable power options.

3.1 Bang-Bang Controller Analysis

The Bang-Bang controller, a simple on-off control mechanism, was implemented in the smart fertigation system to maintain soil moisture levels. This controller operates by switching the water pump on when the soil moisture level falls below a predetermined threshold and turning it off when the desired moisture level is reached. This method is characterized by its straightforward approach, making it easy to implement and understand. Figure 13 show the application of Bang-Bang Control Scheme on Smart Fertigation System.



Fig. 9 Application of Bang-Bang Control Scheme on Smart Fertigation System

The performance analysis of the Bang-Bang controller reveals several critical insights into its operation and efficiency. As depicted in Figure 11, the maximum peak soil moisture level achieved by the Bang-Bang controller is 57%, with the system taking 8.2 seconds to reach this peak. However, the on-off nature of the Bang-Bang controller limits the voltage supply to either 0V or 12V. This binary operation leads to significant overshoot, resulting in overwatering. The system does not immediately correct this overshoot, causing the soil moisture level to exceed the optimal value. It takes approximately 95.8 seconds for the moisture level to drop back to the desired setpoint, during which excess water is used.

This prolonged period of overwatering highlights the inefficiency of the Bang-Bang controller in maintaining precise soil moisture levels. The controller's inability to modulate the pump speed results in water wastage and potential negative effects on plant health. Additionally, the frequent cycling between the on and off states further underscores the limitations of this control method in achieving consistent and efficient irrigation. Consequently, while the Bang-Bang controller offers simplicity and ease of implementation, it falls short in terms of precision and water conservation, necessitating more advanced control strategies for optimal irrigation management.

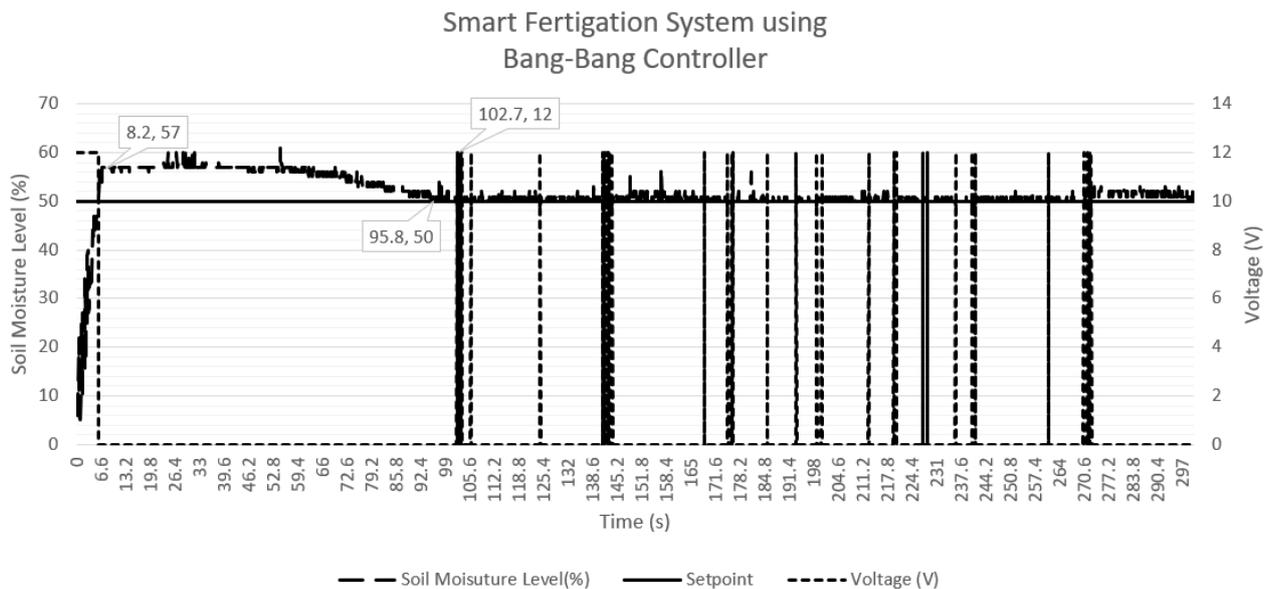


Fig. 10 Graph of Soil Moisture & PID Output versus Time for Bang-Bang Controller

3.2 PID Controller Analysis

PID Control stands for Proportional-Integral-Derivative control. It is a control loop mechanism widely used in industrial control systems. A PID controller continuously calculates an error value as the difference between a desired setpoint and a measured process variable and applies a correction based on proportional, integral, and derivative terms, hence the name. The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant known as the proportional gain, K_p . The integral term is concerned with the accumulation of past errors. If the error has been present for a period of time, the integral term tries to eliminate the residual steady-state error that occurs with a pure proportional controller. The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The derivative term is a prediction of future error, based on its rate of change. It contributes to the control output by considering the rate of change of the error, providing a dampening effect, which can reduce overshoot and improve stability.

Through a systematic trial and error process, each parameter was incrementally adjusted to observe the effects on system performance. The proportional gain was increased to improve the system's responsiveness to current errors. Simultaneously, the integral gain was adjusted to reduce steady-state error and ensure that the desired soil moisture level was maintained over time. The derivative gain was fine-tuned to dampen oscillations and reduce overshoot, leading to a more stable response.

After several iterations, the most effective PID parameters were determined to be $K_p = 7.2$, $K_i = 4$, and $K_d = 1$. These final settings provided a balanced response with minimal overshoot, reduced rise time, and faster settling time. The optimized PID controller ensured that the soil moisture levels were maintained within the desired range efficiently, enhancing the overall performance of the smart fertigation system. This iterative tuning process underscores the importance of careful adjustment and testing to achieve the desired control system performance. Figure 15 show the response graph for smart fertigation system using PID controller.

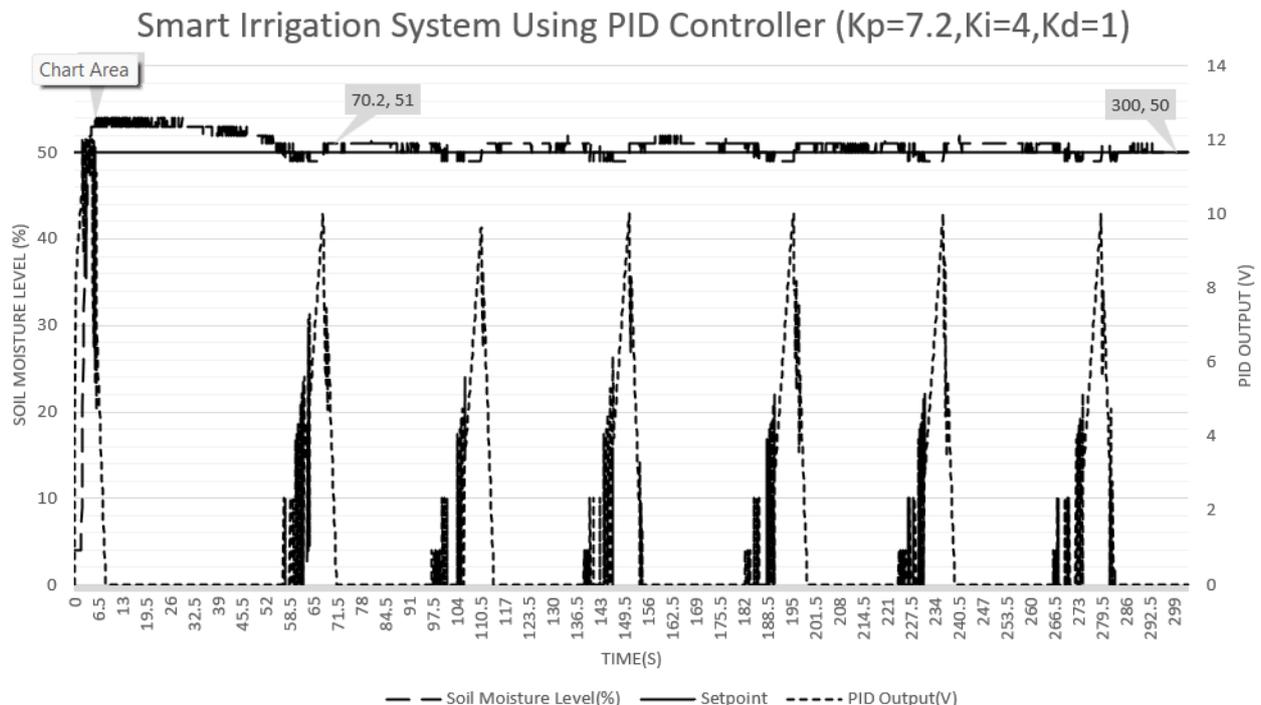


Fig. 11 Graph of Soil Moisture & PID Output versus Time for PID Controller

The PID controller achieves this stability by continuously adjusting the PID output, fine-tuning the operation of the water pump to maintain the soil moisture level within a narrow range around the setpoint. The maximum overshoot observed in the graph is 54%, with a percentage overshoot of 8%. This slight overshoot is quickly corrected by the PID controller, which reduces the soil moisture level back to the setpoint without causing significant water wastage. The controlled and stable nature of the soil moisture level under the PID controller reflects its effectiveness in providing precise irrigation and optimizing water usage.

3.3 Discussion

In the Chapter 3.3 and 3.4, we have testing the performance of smart fertigation system using Bang-Bang controller and PID controller. By analyzing these parameters, we can evaluate how quickly and accurately the system responds to changes in soil moisture levels, ensuring efficient irrigation management. The Rise Time (T_r) and Settling Time (T_s) indicate how responsive and stable the system is, respectively. Percentage Overshoot (%Mp) helps assess overshooting tendencies during transient responses, while RMSE quantifies the overall accuracy of soil moisture predictions compared to actual measurements. These calculations are essential for optimizing control algorithms, fine-tuning system parameters, and improving the overall effectiveness of the smart fertigation system in maintaining optimal soil moisture conditions for crop growth and water conservation.

Table 1 Comparison of Performance when applying Bang-Bang Controller and PID Controller in Smart Fertigation System

Performance of Controller	Rise Time, T_r (s)	Settling Time, T_s (s)	Percentage of Overshoot, %Mp (%)	Root Mean Square Error, RSME (%)
Bang-Bang Controller	7.9	95.8	14	1.41
PID Controller	5.4	70.2	8	1.24

The Bang-Bang controller's performance highlighted its limitations in precision and efficiency. The controller's binary nature (0V or 12V) resulted in a significant overshoot and prolonged periods of overwatering, as the system could not modulate the water flow gradually. The maximum soil moisture level of 57% and the lengthy correction time of 95.8 seconds illustrated the inefficiency of this approach. The frequent cycling between on and off states not only led to water wastage but also stressed the pump and potentially reduced its lifespan. These findings indicate that while the Bang-Bang controller is easy to implement, it is not suitable for applications requiring precise and efficient irrigation control. In contrast, the PID controller demonstrated superior performance in maintaining optimal soil moisture levels. By continuously adjusting the water pump's speed based on the proportional, integral, and derivative components of the control error, the PID controller minimized overshoot and reduced water wastage. The initial parameters ($K_p=1.8$, $K_i=1$, $K_d=0.25$) were refined through trial and error to the most effective settings ($K_p=7.2$, $K_i=4$, $K_d=1$), resulting in improved response times and stability. The PID controller's ability to provide fine-grained control led to more consistent soil moisture levels, highlighting its suitability for precision irrigation applications.

4. Conclusion

The smart fertigation system developed in this project integrates modern IoT technology with efficient irrigation practices to optimize water usage and enhance crop health. By employing the NodeMCU ESP8266 development board, capacitive soil moisture sensor, DHT22 sensor, L298N motor driver, and a 12V DC water pump, the system effectively monitors and controls soil moisture levels. The implementation of the Blynk IoT platform allows for remote monitoring and control, providing users with real-time data and alerts. The system's performance was analyzed under varying environmental conditions, demonstrating its capability to maintain optimal soil moisture levels despite external fluctuations.

This project contributes to the field of smart agriculture by presenting a cost-effective and scalable solution for automated irrigation. The integration of IoT technology with traditional farming practices enhances water use efficiency and reduces labor costs associated with manual irrigation. The use of advanced sensors and controllers ensures precise monitoring and control of soil moisture, which is crucial for the health and productivity of crops. Additionally, the project provides a detailed methodology and practical insights for future implementations, serving as a valuable reference for researchers and practitioners in the field.

Future work on the smart fertigation system could focus on several areas for improvement and expansion. Enhancing the calibration and accuracy of the sensors can provide more reliable data, further optimizing

irrigation schedules. Integrating additional environmental sensors, such as light and CO₂ sensors, could provide a more comprehensive understanding of plant health and growth conditions. Exploring sustainable power options, such as solar panels, could make the system more energy-efficient and suitable for remote or off-grid locations. Additionally, implementing advanced control algorithms, like machine learning, could improve the system's adaptability and efficiency in diverse agricultural settings.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Reference

Journal

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