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## Design of a Smart Chili Mini Greenhouse with ESP32 and Model Predictive Control

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### ABSTRACT

Chili cultivation requires stable environmental conditions to achieve optimal plant growth. However, conventional control methods such as On-Off control are reactive and less efficient in handling dynamic environmental changes. This study develops a mini greenhouse system based on the Internet of Things (IoT) integrated with Model Predictive Control (MPC) to maintain the stability of the microclimate for chili plants. The system uses an ESP32 microcontroller as the main controller, DHT22 and soil moisture sensors to monitor temperature, air humidity, and soil moisture, as well as actuators in the form of a fan and water pump. The MPC algorithm is applied to predict system conditions and determine optimal control actions. The system is also integrated with an IoT platform and Telegram notifications for real-time monitoring. Simulation results show that the MPC method provides more stable temperature control compared to the On-Off control method, with overshoot reduced from approximately  $\pm 2^{\circ}\text{C}$  to  $\pm 0.5^{\circ}\text{C}$  and a faster settling time. Therefore, the developed system can improve microclimate control stability and operational efficiency in a mini greenhouse.

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### INTRODUCTION

Greenhouse is a framed structure enclosed with transparent materials that allow sunlight to enter efficiently, thereby supporting plant growth and production (Nafila et al., 2018). As a controlled growing environment, a greenhouse offers several advantages over open-field cultivation, including protection from pests, reduced exposure to wind and rainfall, improved crop quality control, and the ability to schedule harvesting according to production needs (Yuandari et al., 2021). In addition, microclimate regulation and crop management within a greenhouse can be carried out in a more stable and controlled manner, reducing the risk of crop failure caused by climate variability (I. Putri et al., 2024).

Before a greenhouse is employed for crop production, it is essential to examine the distribution of temperature, humidity, and airflow within the structure

(Megantara et al., 2021). This assessment is important for identifying areas that may be less suitable for plant growth. Suboptimal airflow conditions may adversely affect plant development, as temperature directly influences several physiological processes, including transpiration, respiration, reproduction, ion uptake, and pigment formation (Lestari et al., 2023)(Irfan, 2025). Likewise, humidity affects photosynthesis, leaf development, pollination, and nutrient distribution within plants (Rianti & Prastyo, 2022). Furthermore, dry air and high wind speed may negatively influence crop productivity (Maharani et al., 2018).

Precision agriculture provides a technology-driven approach to improving cultivation efficiency (Atnang et al., 2025). One increasingly developed solution is the Internet of Things (IoT)-based mini greenhouse, which enables real-time monitoring and control of the microclimate (Priono et al., 2022).

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However, many small-scale greenhouse systems still rely on conventional control strategies such as On-Off or PID, which are reactive and less effective in dealing with nonlinear system dynamics (Rianti & Prastyo, 2022)(Sari et al., 2024).

Model Predictive Control (MPC) is an optimization-based control strategy capable of predicting future system behavior and selecting optimal control actions while accounting for system constraints (Schwenzer et al., 2021). This approach is considered more adaptive and efficient than conventional control methods (Faedo et al., 2017). Accordingly, this study aims to design and implement an IoT-based mini greenhouse system using MPC on an ESP32 microcontroller to proactively maintain temperature and humidity stability. The proposed system is expected to improve control efficiency while enabling real-time remote monitoring(Hadi & Jalil, 2026).

Previous studies have explored the application of MPC in greenhouse systems (Lu et al., 2025). Nonlinear MPC has been shown to enhance energy efficiency while maintaining stable temperature and humidity levels in large-scale greenhouses. Robust MPC and data-driven MPC have also demonstrated improved performance under environmental uncertainty, such as weather fluctuations.

Nevertheless, the implementation of MPC in low-cost microcontroller-based mini greenhouses, particularly those using ESP32, remains limited. Moreover, the integration of MPC with IoT systems for small-scale real-time monitoring and notification has not been extensively investigated. Therefore, this study focuses on the efficient implementation of MPC in an IoT-based embedded system for chili cultivation in a mini greenhouse.

## RESEARCH METHOD

This study employed an experimental approach by designing and directly evaluating an IoT-based system integrated with Model Predictive Control (MPC) for a chili mini greenhouse (Gubbi et al., n.d.). In the preliminary stage, the system architecture was developed by specifying the required hardware and software components. The primary hardware consisted of an ESP32 microcontroller, a DHT22 sensor for measuring air temperature and humidity, and a soil moisture sensor (R. E. Putri et al., n.d.). A DC fan was used as a cooling actuator, while a mini water pump served as the irrigation actuator. All components were integrated into a single networked system capable of communicating through the internet(Dirayati et al., 2025).

System operation begins with sensors acquiring environmental data from within the greenhouse. The data are subsequently processed by the ESP32 and transmitted to a web-based or cloud-based monitoring platform, enabling real-time observation(Priyonggo et al., 2023). This framework is consistent with the application of IoT in agriculture, which facilitates remote monitoring and control.

Within the MPC framework, a simplified greenhouse model is constructed, such as the relationship between temperature and fan actuation or between humidity and water pump operation. The system then utilizes this model to predict future conditions (P et al., 2024). Based on the predicted outcomes, the controller determines the most appropriate action, such as activating the fan or initiating irrigation. This approach was selected because it is more proactive than conventional control methods, as it not only responds to current conditions but also anticipates future system behavior(Sari et al., 2024).

The IoT system was further integrated with a monitoring interface, such as a web dashboard or a simple application, allowing users to observe temperature, humidity, and soil conditions in real time(Lestari et al., 2026; Muhammad Zikri et al., 2025). Previous studies have demonstrated that IoT-based greenhouse systems can enhance operational efficiency and maintain optimal growing conditions (Gubbi et al., n.d.). System performance was evaluated by observing its response to environmental changes, such as increasing temperature or decreasing soil moisture. In addition, a comparative assessment was conducted between the MPC-based system and a conventional on/off control system. The evaluation parameters included temperature stability, humidity control, and response time (Lestari et al., 2023).

## RESULTS AND DISCUSSION

This chapter presents the results of the design and implementation of an IoT-based chili mini greenhouse system, along with a discussion of the system's operation and performance in automatically controlling environmental conditions. The discussion covers the needs analysis, system design, and the architecture used.

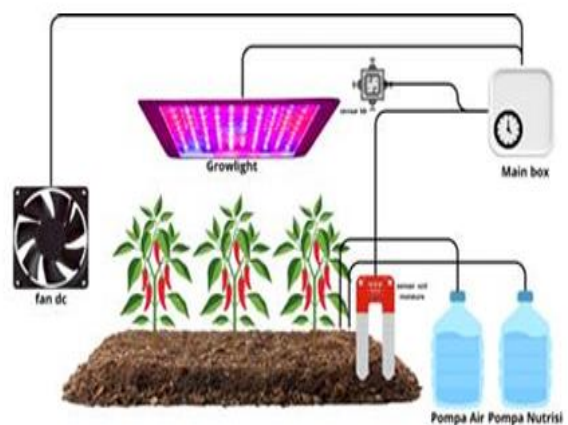


Figure 3.1 (a) Design of an IoT-Based Mini Greenhouse System

Figure 3.1(a) Mini Greenhouse System Design. The figure shows the mini greenhouse layout, including the main control box, a DC fan for air circulation, a grow light as an additional light source, and water and nutrient pumps to support irrigation and

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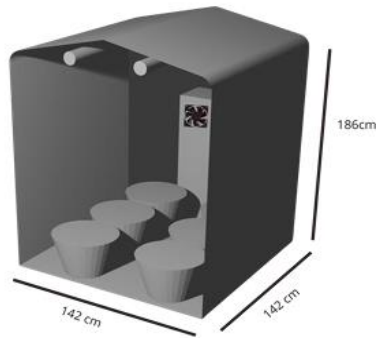


Figure 3.1(b) Placement Layout of the Mini Greenhouse.

Figure 3.1(b) Mini Greenhouse Placement Layout. The figure shows the physical placement and dimensions of the mini greenhouse, with a length and width of 142 cm and a height of 186 cm.

### 1. System Architecture Design

The developed system is structured into three interconnected main layers. Each layer has its own function, ranging from data acquisition and information processing to automatic control action execution. These three layers operate continuously to ensure that the greenhouse environment remains stable and suitable for plant growth. The system consists of three main layers:

#### a. Sensing Layer

Sensors periodically read the environmental conditions.

#### b. Processing Layer

The ESP32 processes the collected data using the MPC algorithm to predict future conditions and determine the optimal control action.

#### c. Actuating Layer

The actuators respond to the control commands to maintain microclimate stability.

### 1.1 Prediction

The system predicts future outputs using a discrete mathematical model:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned}$$

### 1.2 Optimization

The cost function is minimized:

$$J = \sum_{j=1}^{N_p} \|y(k+j|k) - r(k+j)\|_Q^2 + \sum_{j=0}^{N_c-1} \|\Delta u(k+j|k)\|_R^2$$

where:

- $yy$  = system output
- $rr$  = setpoint

- $uu$  = control action
- $N_p$  = prediction horizon
- $N_c$  = control horizon
- $Q$  and  $R$  = weighting factors

### 2. IoT Integration and Notification System

MPC operates based on the following principles:

Sensor data are transmitted via a Wi-Fi connection to an IoT platform for real-time visualization and are also processed as input for decision-making. In addition, the system automatically sends notifications through Telegram when critical conditions are detected, such as temperature exceeding the safe limit, soil moisture falling below the minimum threshold, or network connectivity disruptions.

### 3. System Scenario Diagram

The system begins with Wi-Fi configuration. If the connection is successful, the data are sent to the IoT platform. Otherwise, the system repeats the connection process until it is established. After the connection is active, the system reads data from the light intensity sensor, soil moisture sensor, and temperature and air humidity sensor. The real-time clock is used to support time-based operation. Based on the sensor readings, the system processes the control logic using NMPC. The output actions include activating the water pump, nutrient pump, and grow light, as well as the DC fan. All data are then sent to the IoT server, and Telegram notifications are delivered when required.

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This study successfully designed and implemented an IoT-based mini greenhouse system using the Model Predictive Control (MPC) algorithm on an ESP32 microcontroller. Based on the initial simulation results, MPC demonstrated more stable control performance than the conventional On-Off method, with lower overshoot and error, as well as a faster settling time. The integration of the system with an IoT platform and Telegram notifications enabled real-time monitoring and response to environmental changes. The developed system has the potential to improve microclimate control efficiency in small-scale chili cultivation and urban farming.

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