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# Development of Tropical Grape Greenhouse Monitoring and Nutrient Delivery Scheduling using MQTT Protocol and IoT

***Perancangan Sistem Monitoring dan Penjadwal Pemberian Nutrisi tanaman Anggur di dalam Greenhouse dengan Protokol MQTT dan IOT***

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**ABSTRACT**

Grape production in Indonesia is limited due to environmental conditions and other factors. However, grape consumption in Indonesia has become popular over the last decade. Nutrient and water delivery are scheduled based on the growth stages of the grape, which consist of vegetative and generative stages. Those dynamic schedules should be assisted using automatic monitoring and controlled using the message queuing telemetry transport (MQTT) and Internet of Things protocol. However, the performance of monitoring and control should be evaluated. This study aimed to evaluate the performance of Tropical Grape Greenhouse Monitoring and Nutrient Delivery Scheduling using the MQTT protocol and IoT technique. The research stages include system analysis, design, implementation, and testing. The outcomes of this study consist of a monitoring system and a control system. The monitoring system is equipped with a main control unit (MCU) based on an ESP32, along with sensors for air temperature and humidity (DHT21), light intensity (lux sensor), water temperature (DS18B20), and soil moisture. Data is transmitted via an Aedes-based MQTT broker installed on the Node-RED platform on a virtual private server (VPS) integrated with a MySQL database. The monitoring and control system is implemented in the grape greenhouse at the Agribusiness and Technology Park (ATP) at IPB University. Specifically, the control system is designed and implemented in the grape greenhouse to activate solid-state relays (SSRs) and contactors to operate water pumps and solenoid valves, all managed through a dashboard interface. System performance testing was conducted to evaluate reliability and latency at MQTT quality-of-service (QoS) levels using the one-way delay (OWD) method. The results indicate that the monitoring node's latency at QoS 0 is relatively stable, averaging 59.51 milliseconds. For the control system, the average latency test was 63.07 milliseconds for QoS 0, 72.21 milliseconds for QoS 1, and 85.64 milliseconds for QoS 2.

**Keywords:** ESP32; greenhouse; MQTT; quality of service

***ABSTRAK***

*Produksi anggur di Indonesia masih terbatas akibat kondisi lingkungan dan berbagai faktor lainnya. Namun, konsumsi anggur di Indonesia meningkat pesat dalam satu dekade terakhir. Penjadwalan pemberian nutrisi serta pemantauan kondisi lingkungan, seperti suhu dan kelembapan udara, merupakan aspek yang sangat penting. Pemberian nutrisi dan air dijadwalkan berdasarkan fase pertumbuhan tanaman anggur, yang meliputi fase vegetatif dan generatif. Penjadwalan yang bersifat dinamis ini perlu didukung oleh sistem pemantauan otomatis serta pengendalian berbasis Message Queuing Telemetry Transport (MQTT) dan teknologi Internet of Things (IoT). Namun demikian, kinerja sistem pemantauan dan pengendalian tersebut perlu dievaluasi. Penelitian ini bertujuan untuk mengevaluasi kinerja sistem pemantauan greenhouse anggur tropis serta penjadwalan pemberian nutrisi berbasis protokol MQTT dan teknologi IoT. Tahapan penelitian meliputi analisis sistem, perancangan, implementasi, dan pengujian. Hasil penelitian berupa sistem pemantauan dan sistem pengendalian. Sistem pemantauan dilengkapi dengan unit kendali utama (MCU) berbasis ESP32, serta sensor suhu dan kelembapan udara (DHT21), intensitas cahaya (sensor lux), suhu air (DS18B20), dan kelembapan tanah. Data ditransmisikan melalui broker MQTT berbasis Aedes yang diinstal pada platform Node-RED di virtual private server (VPS) yang terintegrasi dengan basis data MySQL. Sistem pemantauan dan kontrol diimplementasikan pada greenhouse anggur di Agribusiness and Technology Park (ATP), IPB University. Secara khusus, sistem pengendalian dirancang dan diimplementasikan untuk mengaktifkan solid-state relay (SSR) dan kontaktor dalam mengoperasikan pompa air serta katup solenoid, yang seluruhnya dikendalikan melalui antarmuka dashboard. Pengujian kinerja sistem dilakukan untuk mengevaluasi reliabilitas dan latensi pada berbagai tingkat Quality of Service (QoS) MQTT menggunakan metode one-way delay (OWD). Hasil penelitian menunjukkan bahwa latensi pada node pemantauan pada QoS 0 relatif stabil dengan rata-rata sebesar 59,51 milidetik. Pada sistem pengendalian, rata-rata latensi yang diperoleh adalah 63,07 milidetik untuk QoS 0, 72,21 milidetik untuk QoS 1, dan 85,64 milidetik untuk QoS 2.*

***Kata Kunci:*** *ESP 32; greenhouse; MQTT; quality of service*

## INTRODUCTION

Grapes (Vitis vinifera L.) are among the most extensively produced fruit crops worldwide, valued both for fresh consumption and as raw material for processed items such as raisins, juice, and wine. Grape production in the tropics has received increasing attention due to increased demand for quality fruits and the potential for diversification of agricultural commodities. However, grape production in the tropics is faced with some of the following limitations, including high rainfall, temperature fluctuations, and high humidity, which may hurt vine development, fruit quality, and production (Kwizera et.al., 2021). To counter these limitations, protected cultivation facilities such as greenhouses are gaining prominence as a way of creating a more desirable microclimate for grape production

Greenhouses are a building for cultivation the plant purposed to reduce the intervention from pests and diseases from outside areas (Erniati et.al., 2023). Greenhouse structures consist of a transparent roof, a screen in the side wall, and a floor. Several greenhouses are also equipped with automatic nutrient control and delivery (Jamil et.al., 2022). Nutrient delivery systems are a configuration of a pump and a delivery system, such as drip or hydroponically using circulated water for nutrient film techniques (NFT) (Supriyanto et.al., 2025). In a tropical area, cultivation inside the greenhouse is influenced by solar radiation that increases the temperature inside the greenhouse. Higher temperatures are unwanted conditions for farmers that can be caused damages of plant. There are several methods to reduce the temperature inside the greenhouse, such as utilizing the misting system, evaporative cooling systems, and several cooling systems (Kim et.al., 2023). However, the limitation of cooling system is the capacity of the system to reduce the temperature.

The main feature in a greenhouse is a monitoring and controlling system to manage the greenhouse conditions. The monitoring system inside the greenhouse is mainly to capture the temperature, air humidity, soil humidity, and soil temperature. That information is the main parameter in determining the control system applicable to greenhouse applications. Then, the control system mainly consists of an electrical connector to the pump, an electrical connector to the solenoid valve, and a microcontroller in a node of the greenhouse. Those systems are implemented inside a modern greenhouse (Erniati et al., 2023). However, there are still limitations of scalability and the data speed transfer to communicate all customized hardware inside the greenhouse.

Internet of Things technology (IoT) is a configuration of newest technologies in data communications, especially in greenhouse applications. IoT is a main tool for sensors, microcontrollers, servers, communication hardware, networks, and human interaction with the system. Human interaction is a main feature included in the user interface (UI) to show the monitored data and control the actuators that provide the controlled conditions (Jamil et.al., 2022). However, several communication protocols can be applied on monitoring and controlling a greenhouse inside the greenhouse (Kashyap et.al., 2024). Mainly, a small-scale system utilizes the hypertext transfer protocol (HTTP) utilized in small scale monitoring and control. However, those technologies are not reliable for large-scale and lower speed performance. To overcome these limitations, light-weight communication architectures are required. MQTT is a lightweight, publish-subscribe messaging protocol designed specifically for constrained devices and low-bandwidth, high-latency networks.

Despite the growing adoption of IoT in smart farming, a research gap remains in evaluating real-time, low-latency MQTT control architectures for high-precision and multi-actuator irrigation. Most existing implementations focus either on static parameter monitoring or simple HTTP-based single-actuator loops. In this research, we proposed a message queuing telemetry transport (MQTT) IoT platform implemented on a grape cultivation greenhouse. This research focused on the development of monitoring and controlling a grape cultivation greenhouse using MQTT as an IoT platform. The system will be evaluated and evaluated in a real greenhouse at Agribusiness and Technology Park (ATP) IPB University. solenoid valves to determine the nutrient delivery volume and time scheduling.

## METHODOLOGY

In this study, a monitoring and nutrient delivery scheduling using MQTT and the Internet of Things was implemented and evaluated using several stages, such as: (i) user requirement analysis, (ii) system design, (iii) hardware and software construction, (iv) system implementation, and (v) performance evaluation (Fig 1).

### User Requirements Analysis

During the system analysis stage, the functional requirements of the monitoring and control system in greenhouses and plant factories were identified. This process included literature studies, field observations, and needs analysis for each greenhouse and plant factory. In addition, the environmental parameters to be monitored were determined, namely air temperature and humidity, light intensity, soil moisture, and water (solution) temperature. At this stage, the actuator devices to be controlled were also determined, namely pumps and solenoid valves. Analysis of the hardware and software system for monitoring and control hardware, Node-RED flow, database, backend, and frontend on the user interface. The results of this stage form the basis for the overall system architecture design.

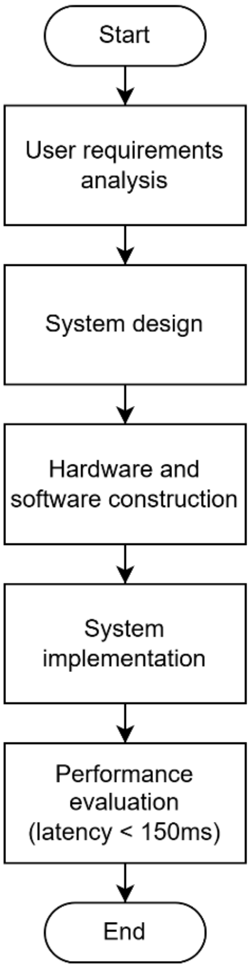


Figure 1. Research flow of study

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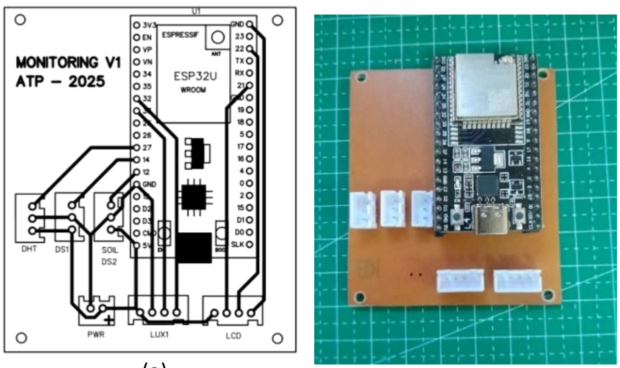
**System Design**

At this stage, a comprehensive system architecture was developed, covering both hardware and software components. The design process included the selection of an appropriate microcontroller (MCU), sensors, and actuators to support environmental monitoring and control in greenhouse and plant factory applications. The data communication flow was structured using the MQTT protocol, defining topic schemes, publishers, and subscribers. In addition, a user interface was designed to facilitate data visualization and device control. To illustrate the system workflow, component diagrams, process flowcharts, and data flow diagrams were employed, serving as references for the implementation and testing phases. The system design in this study specifically emphasizes the performance of the MQTT protocol in terms of latency (delay).

**Hardware and Software Construction**

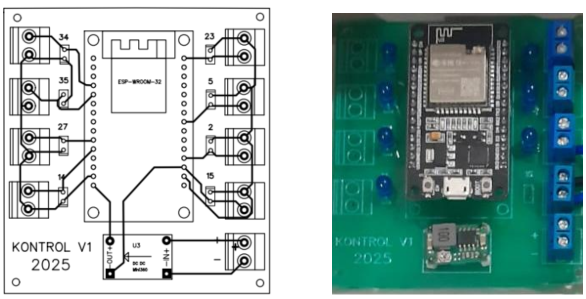
In this stage, both hardware and software were developed for the monitoring and nutrient delivery system. The hardware development for the monitoring system included the fabrication of the printed circuit board (PCB) and electrical assembly. The PCB was designed to integrate the ESP32, DHT sensor (air temperature and humidity), lux sensor (light intensity), soil moisture sensor, liquid crystal display, and a push button (Fig 2a). The PCB was fabricated using FR2 material with a single-layer configuration (Fig 2b).

The PCB for nutrient control was designed with the ESP32 as the main controller unit, connected to up to eight relay channels through digital outputs (Fig. 3a). The PCB was fabricated using FR4 material with a double-layer configuration (Fig. 3b). The system was powered by an adapter that converts 220 VAC to 12 VDC. The software development included firmware programming for the ESP32, virtual private server (VPS) configuration, Node-RED flow setup, database configuration, and user interface design.




(a) (b)

Figure 1. Layout of PCB: (a) PCB design and (b) fabrication




(a) (b)

Figure 2. Layout of PCB: (a) PCB design and (b) fabrication


Figure 3. Latency measurement scheme on sensor nodes


Figure 4. Latency measurement scheme on control nodes

**System Implementation**

The system was implemented in a grape greenhouse located at the Agribusiness and Technology Park, IPB University. The monitoring node was equipped with sensors capable of measuring key environmental parameters, including air temperature and humidity, light intensity, and soil moisture. The soil moisture sensor was installed directly in the grape growing medium. The control system was designed to operate the irrigation pump and to regulate the selection between water and nutrient solutions.

**Performance Evaluation**

In this research, the performance evaluation mainly focuses on the latency of the data transmission. Latency in the MQTT communication protocol consists of queuing, processing, channel link establishment, transmission, routing, and propagation processes, as expressed in the following equation (Kenitar et.al., 2018).

$$L = T_q + T_{pr} + T_e + T_t + T_r + T_{prg} \quad (1)$$

The latency testing method in this study implemented the one-way delay (OWD) approach. Latency in the system is calculated using timestamp comparison between the moment the publisher sends the payload and the moment the subscriber receives the payload (equation 2).

$$L = T_{recieve} + T_{send} \quad (2)$$

The testing of the monitoring system involves communication from the sensor node to Node-RED. The sensor node functions as the publisher of sensor data, while Node-RED acts as the subscriber. The payload transmitted by the sensor node includes a timestamp (Fig 4). This test aims to measure how fast sensor data can reach the monitoring system, as well as to evaluate the stability of communication through the MQTT protocol.

The control system testing involves the website user interface (UI) and the control node. The UI functions as the publisher of commands, while the control node acts as both a subscriber and a publisher. Fig 5 illustrates the testing process, where the UI publishes commands along with a timestamp, and the control node subscribes and subsequently publishes the reception time to the MQTT broker. Time synchronization is managed using the Network Time Protocol (NTP). This control system testing is carried out using variations of the Quality of Service (QoS) levels available in the MQTT protocol (QoS 0, QoS 1, and QoS 2). A maximum latency threshold of 150 ms was established as the criterion for successful control command transmission to meet ETSI standard (1999).

## RESULT AND DISCUSSIONS

### Implementation of Greenhouse Monitoring

The monitoring system consists of hardware and software components. The hardware system includes sensor nodes that can measure environmental parameters, such as air temperature and humidity, light intensity, and soil moisture. Each sensor node is an embedded system composed of sensors, an MCU, a liquid crystal display (LCD), and a power supply. All sensors are connected to the ESP32 MCU through hard-wired connections, as shown in Figure 6.

All components were housed in an IP66-rated Durabox enclosure, with dedicated openings for the LCD, sensors, antenna, and power supply to support reliable system operation. The sensor node was mounted on a greenhouse pole with careful consideration of sensor placement to ensure accurate environmental measurements (Fig. 7a). At this implementation stage, the soil moisture sensor was embedded in the grape growing medium to monitor moisture levels of the planting substrate, which is integrated with an irrigation system (Fig. 7b).

The sensor node reads environmental parameters at a fixed sampling interval of 2 seconds. The acquired sensor data are processed by the ESP32 microcontroller and formatted before transmission. Subsequently, the data are sent wirelessly via a Wi-Fi connection to an MQTT broker integrated with the Node-RED platform. The data transmitted to the Node-RED broker is first subjected to a buffering process, during which sensor readings are collected and averaged over a 10-minute interval to reduce noise and short-term fluctuations. At the end of each 10 minutes, the processed data is structured and formatted according to the database schema. The formatted data are then transmitted to a MySQL database using the Hypertext Transfer Protocol (HTTP) POST method through an Application Programming Interface (API) endpoint hosted on a VPS. Figure 8 shows the flow process in the Node-RED application.

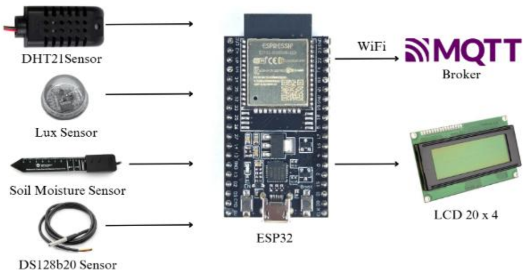



Figure 5. Hardware architecture

(a) (b)

Figure 6. Implementation of (a) monitoring hardware and (b) soil moisture sensor

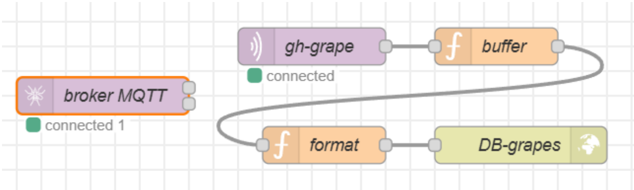



Figure 7. Data handling on Node-RED

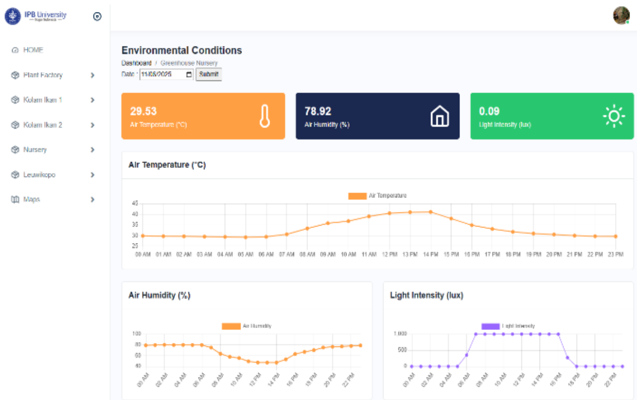



Figure 8. Web Dashboard for Display monitoring parameters such as air temperature, air humidity and light intensity

The data stored in the MySQL database are subsequently accessed and processed by a PHP-based application to be read and displayed on a web-based front-end interface. The monitoring dashboard provides users with real-time and historical visualization of environmental parameters, allowing the selection of specific dates for detailed analysis. In addition, user-defined threshold values can be configured to support monitoring and decision-making processes. An example of the monitoring dashboard interface is presented in Fig. 9 below.

### 3.2 Implementation of Nutrient Delivery Scheduling

A pump is used to deliver the solution into the piping network for distribution to the grape plants. Solenoid valves are employed to select the type of solution to be supplied (Fig 10b). The control node is connected to relays installed in the control panel, and these relays subsequently regulate the operation of the solenoid valves and the pump contactor (Fig 10a). There are two control modes in this system, manual mode and automatic (auto) mode.

The manual mode allows users to directly activate the system components, including the pump and solenoid valves, either through a web-based user interface (Fig 11) or via physical buttons on the control panel. In the automatic mode, users can configure scheduled irrigation using water and nutrient solutions based on predefined time settings with repeatable operation. The automatic mode was set to execute twice daily at 08:00 AM and 04:00 PM with each valve operating for a duration of 10 minutes per zone. The transmission of control commands from the web interface to the control node is carried out using the MQTT protocol with quality of service (QoS) level 1. The implementation of QoS level 1 is intended to ensure that control commands are successfully received and acknowledged by the control node (hardware). This method provides an “at-least-once” delivery guarantee, ensuring every control payload is successfully acknowledged by the control node to prevent missed irrigation cycles.

### 3.3 Performance Evaluation

The testing process was conducted by transmitting the sending timestamp from the MCU sensor node (Tsend) to the

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MQTT broker. The latency measurement results from 50 trials indicate an average latency of 59.51 ms, with a minimum value of 28 ms and a maximum value of 101 ms (Fig 12). Internet network stability was identified as the primary influencing factor, followed by the inherent characteristics of QoS 0.

Fundamentally, QoS 0 operates based on the fire-and-forget principle, meaning that no retry mechanism or acknowledgment (ACK) is provided. Therefore, there is no guarantee that the message is successfully received (Chen et al., 2024). Buffer accumulation may occur because the TCP mechanism continues attempting to transmit information through the publishing method. Since QoS 0 does not wait for a response, the ESP32 continuously sends data to the socket even when the socket has not been fully cleared (Kashyap et.al., 2024).

The evaluation process of the control system involved the user interface (UI) and the control node, with three variations of QoS levels: 0, 1, and 2. The latency test results of the MQTT protocol indicate significant differences among the three QoS levels. QoS 0 exhibited a latency range between 8 ms and 118 ms, QoS 1 ranged from 19 ms to 133 ms, and QoS 2 ranged from 15 ms to 179 ms. On average, QoS 0 demonstrated lower latency compared to QoS 1 and QoS 2 (Fig 13).

(a) (b)

Figure 9. Implementation of (a) panel control and (b) piping system

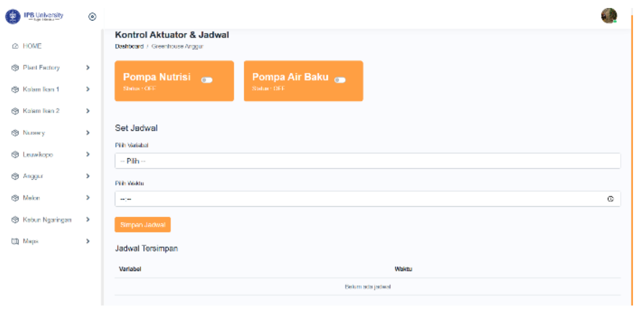


Figure 11. Web Interface design for Nutrient delivery scheduling

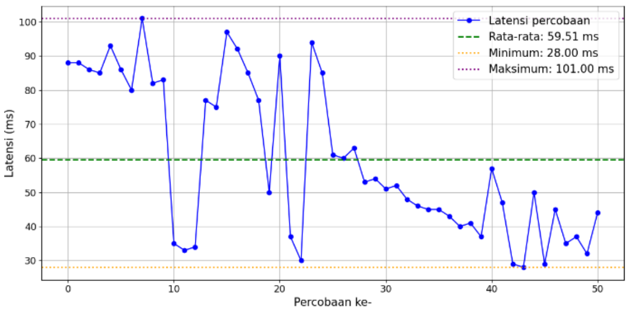


Figure 12. Latency evaluation of the monitoring system

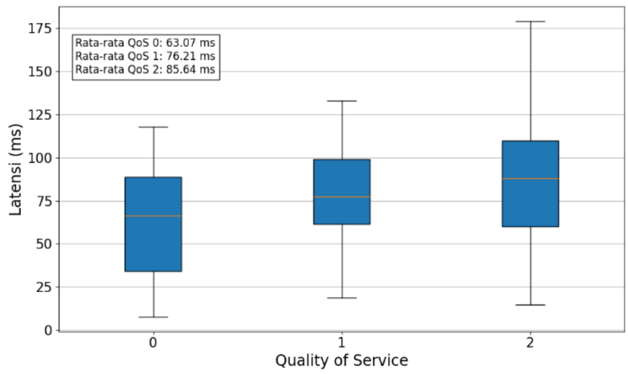


Figure 13. Latency evaluation of the control system

Referring to the ETSI latency standard (1999), the average latency values for all QoS variations in this study fall within the “best” category (<150 millisecond). The lower latency observed in QoS 0 is attributed to the absence of acknowledgment mechanisms, resulting in faster transmission but without delivery guarantees. QoS 1 (*at least once*) produces higher latency due to the acknowledgment mechanism from the subscriber. Meanwhile, QoS 2 (*exactly once*) exhibits the highest latency because it involves a two-phase handshake process (PUBREC, PUBREL, and PUBCOMP) to ensure that messages are not duplicated (Saha et.al., 2024). The obtained data demonstrates a trend consistent with the findings of Hintaw (2025), which indicate that increasing the QoS level in MQTT directly contributes to higher latency due to additional communication overhead required to guarantee message delivery reliability. QoS 2 employs a bidirectional handshake process to prevent duplicate message transmission, thereby enhancing reliability at the expense of transmission speed (Hintaw, 2025). Therefore, the selection of the QoS level is crucial, as it directly affects the trade-off between communication speed and reliability.

## CONCLUSION AND FUTURE WORK

The system development was completed, consisting of hardware components (sensor node and control node) and software components (Node-RED, database, and user interface). The monitoring and control nodes utilize the ESP32U as the microcontroller unit (MCU), functioning as an MQTT client. The MQTT broker is implemented using Node-RED and is operated on a Virtual Private Server (VPS). The latency testing results for the monitoring system under QoS 0 demonstrate stable performance, with an average latency of 59.51 milliseconds. In the control system latency evaluation, QoS 0 achieved an average latency of 63.07 milliseconds, QoS 1 recorded 72.21 milliseconds, and QoS 2 resulted in 85.64 milliseconds. All QoS configurations comfortably fell below the 150 ms threshold, placing the system within the "best" latency performance category according to the ETSI standard (1999). This confirms that the proposed architecture achieves highly acceptable real-time responsiveness and network reliability for automated greenhouse control. For future work, it is recommended to evaluate the system's performance under constrained or fluctuating edge-network conditions, such as low-bandwidth cellular connections.

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