Design and Implementation of Rule-Based and Time-Based Logic in a PAC-Based Precision Irrigation Control System

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***Abstract*—This study aims to design and functionally validate a prototype precision fertigation control system based on a Programmable Automation Controller (PAC) capable of managing water and nutrient delivery through two approaches: a time-based approach as the basic control and a rule-based approach as a corrective response based on sensor data (pH, EC, and moisture) of the growing medium. The method used in this study is Research and Development (R&D), and the scope of the research is limited to the Preliminary Field Testing phase, which includes requirements gathering and literature review, architectural planning (sensors, gateway, PAC, actuators, HMI/Human Machine Interface), development of an initial prototype (hardware and software), as well as initial-scale functional testing through hardware functional testing and black-box testing on the HMI interface. The test results showed that all acceptance criteria were met, including sensor function deviation of 2.5% (≤5%), actuator response time of 1.2 s (<2 s), current deviation of 2.0 A (≤3 A), voltage stability of 12.1 V (11.4–12.6 V), operational reliability of 96 hours (≥72 hours), communication success rate of 99.5% (≥99%), and system response latency of 320 ms (<500 ms); all results were classified as Pass. Thus, the developed prototype has proven to be stable and suitable for initial field testing, and provides a solid foundation for further development toward broader application in more efficient and responsive fertigation management.**

***Keywords*—HMI; precision fertigation; PAC; preliminary field testing; time-based control; rule based control**

I. Introduction

Terminologically, fertigation is often regarded as an intrinsic element of hydroponic systems. However, within the broader scope of agronomy, this technology is a technique for delivering soluble nutrients through an irrigation system that can be applied across various growing media [1]. The application of fertigation in crop cultivation using drip fertigation (drip irrigation) in soil or non-hydroponic substrates represents an evolution of precision agriculture [2]. Fertigation is a crop cultivation method that combines irrigation and fertilization, in which nutrients are delivered simultaneously with irrigation water in a measured and timely manner. This method offers high efficiency in water and nutrient use, which directly impacts the improvement of crop yield quality and quantity [3]. Fertigation is a highly effective and increasingly popular approach in crop cultivation.

In fertigation-based crop cultivation, "treatment" often refers to variations in the dosage, frequency, or composition of nutrients provided to plants. Plant treatments may involve applying specific conditions or inputs to plants to observe their impact on growth and yield [4][5]. The concept of "treatment" plays a crucial role; in fertigation, it represents an approach to water management and distribution that integrates essential nutrients dissolved directly into the plant's root zone via the irrigation system. Plant treatment is not merely separate watering or fertilizing, but rather a precise, integrated process. A "treatment" in fertigation can encompass various variables, including: 1) Type and Concentration of Nutrients; 2) Volume and Frequency of Application; 3) Application Timing (nutrient delivery). The objective of treatment in the fertigation method is to ensure that plants receive the optimal amount of water and nutrients at the right time, thereby improving nutrient use efficiency, conserving water, and maximizing crop yields.

Effective fertigation methods require high precision, and this is where control technology is essential. In previous studies, IoT (Internet of Things) technology has been widely used to monitor and control fertigation. Some of these studies include: Microcontroller- and HMI-based IoT applications to support agricultural control systems [6]. The use of cloud-server-based IoT for fertigation control [7]; in this study, the system was highly dependent on the internet. The use of IoT and fuzzy logic to support irrigation systems [8] [9] [42] [43]; this study did not account for plant growth phases. The use of IoT to improve the efficiency of nitrogen and EC use in drip-fertigation systems [10] [11]; this did not account for errors in sensor readings [41].

The current trend in precision agriculture is that data has become the key factor enabling automation, intelligent analysis, and more efficient decision-making. On the other hand, agricultural research generates a wealth of data regarding optimal nutrient doses, timing of nutrient application, ideal growing medium conditions (pH/EC/moisture), and specific

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plant requirements at various growth stages [12]. This data and information are often complex and require agronomic expertise to interpret.

This study aims to design, develop, and verify an HMI (Human Machine Interface) application program to execute and monitor two plant treatment methods: time-based (plant treatment based on time/schedule) and rule-based (serving as both a quick correction and a safety limit monitor) within a PAC (Programmable Automation Controller)-based control system, thereby enabling the regulation of water and nutrient supply based on sensor data in the growing medium.

A PAC is a control system that combines the functionality of a programmable logic controller with more modern and flexible computing capabilities, similar to a personal computer (PC). The main contributions of this research are: 1) developing an HMI as an interface between the user and the fertigation control system, 2) implementing two plant treatment modules (time-based and rule-based) integrated into the fertigation control system, and providing facilities for monitoring the fertigation process via the HMI.

II. Method

This study employs a Research and Development (R&D) methodology, which emphasizes the design and construction of prototypes, as well as prototype evaluation [13]. The focus of the study is to produce a prototype HMI application program and a plant treatment logic control system (time- and rule-based), which has been functionally validated through preliminary field testing.

A. Research and Development (R&D) Methodology

Fig. 1 shows the block diagram of the R&D stages conducted in this study, namely: 1) Research and Information Collection: this stage gathers requirements and foundational knowledge to design a precision fertigation control system through literature reviews, growing medium data (pH, EC, moisture) as indicators of plant health and fertility, and PAC architecture. 2) Planning: This stage establishes the technical design and prototype plan, including system architecture, as well as initial functional test scenarios as success criteria; 3) Developing a Preliminary Product Form: This stage produces an initial prototype of a PAC-based fertigation control system integrated with control logic and HMI software, 4) Preliminary Field Testing: This stage involves simulation testing to ensure the prototype functions properly and is ready for further development.

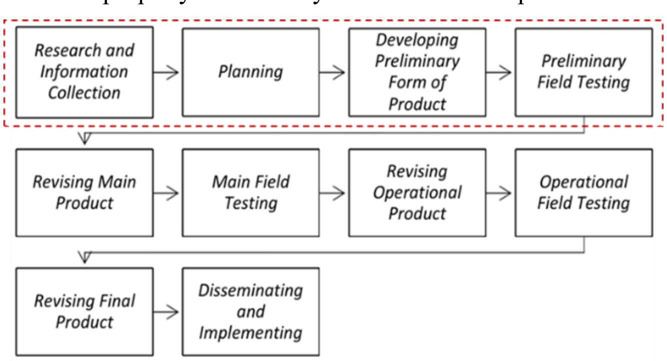

Fig. 1. Stages of the R&D methodology.

1) Concept of plant treatment using the fertigation method: In fertigation, "treatment" refers to the planned, measured, and controlled application of a mixture of irrigation water and nutrient solution directly to the plant's root zone. This treatment is not merely ordinary watering or fertilizing, but rather a precise, integrated management of plant needs [14]. Treatment is at the core of the fertigation method, where an integrated system delivers the primary supplies of water and nutrients directly to the plants. The fertigation method integrates four planned actions: 1) formulating nutrients, 2) determining dosage and concentration, 3) regulating timing and frequency, and 4) selecting the treatment method. Thus, treatment in the fertigation method involves the measured management of water and essential nutrient delivery, thereby enhancing the accuracy, efficiency, and responsiveness of agriculture to achieve optimal crop yields.

This study developed two integrated control methods: time-based control and rule-based control. In time-based control, the system relies entirely on a schedule predefined by the operator or farmer. In the rule-based treatment, the system relies on conditional logic (if-then) triggered by real-time data from EC, pH, and growing medium moisture sensors. Rule-based treatment is applied only when the plants need it, thereby preventing waste and optimizing growth. This system is far more efficient and responsive to daily weather changes, resulting in more efficient resource use and more consistent crop yields. An example of a rule-based treatment is: "IF the growing medium moisture is below 60% OR solar radiation exceeds a certain threshold, THEN activate the actuator until moisture reaches 85%."

2) PAC-based fertigation control system: Effective fertigation methods require high precision, so control system technology is essential. The fertigation control system serves as an operational hub that ensures the treatment is carried out as planned. This system is responsible for opening valves and activating pumps. Consequently, to execute these various actuator operations, accurate and reliable hardware is required. The PAC integrates various functions, including: 1) Data Acquisition: The PAC connects to a network of field sensors to monitor growing media conditions in real-time; 2) Data Processing: The PAC runs complex algorithms, including both time-based treatment logic and rule-based treatment logic (if-then) to interpret sensor data; 3) Coordinated Control: Based on the interpretation of sensor data, the PAC precisely controls the actuators to implement the required treatment activities.

B. Design and Development: Prototype of the Complete System

Fig. 2 shows the architecture of a PAC (Programmable Automation Controller)-based irrigation control system, which consists of: 1) Data Processing, 2) Control Panel, 3) Actuators, and 4) WSN (Wireless Sensor Network). Table I shows the functions of each component within the PAC.

TABLE I. COMPONENTS, FUNCTIONS, AND DEVICE REQUIREMENTS OF THE PAC

Components	Functions	Requirement
PC/Laptop	Data Processing	1. OS: Windows 10 2. RAM: 8 MB 3. Hard disk: 120 GB
Control Panel	The control panel serves as a hardware integration hub that connects the actuators to the data processing PC, ensuring that the sensing–decision–actuation process runs smoothly.	4. ADAM 4520: RS-232 to RS-485 Converter 5. ADAM 4017/18: Analog Sensor Input, 8 channels 6. ADAM 4068: Relay Output, 8-channel relay-based
Actuator	The actuator serves as an execution component that converts control decisions from the PC into physical actions in the fertigation process.	7. Relay: 12V DC, 8-pin
Wireless Sensor Network	Continuously measures the EC, pH, and humidity parameters in the growing medium.	Soil sensor 7-in-1, 12–24 V, DC RS485 module; Gateway

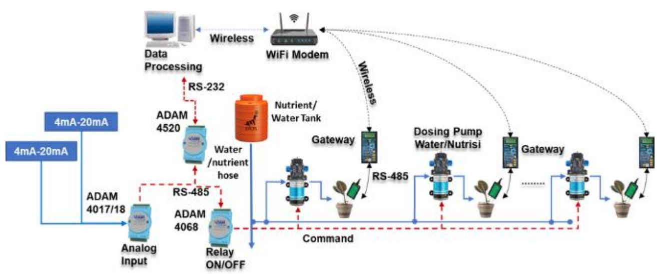

Fig. 2. Architectural design of the fertigation control system.

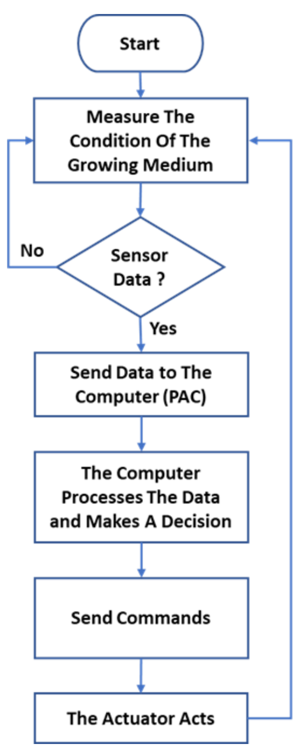

Fig. 3. Flowchart of how the fertigation control system works.

Fig. 3 shows a block diagram of how the PAC-based fertigation control system works. Overall, this fertigation control system operates in a single feedback loop: measure conditions --> send data to the computer (PC) --> the computer processes the data and makes a decision --> send a command --> the actuator responds.

1) Data processing: The Data Processing unit is the central data processing component within the PAC (Programmable Automation Controller), responsible for executing logic control instructions [28], processing data from the WSN (Wireless Sensor Network) [15], and managing communication with actuators. In this study, the Data Processing Unit consists of a PC running the Windows 10 operating system, which enables it to handle more complex algorithms to support the operation of the Logic Control and HMI (Human Machine Interface) application programs.

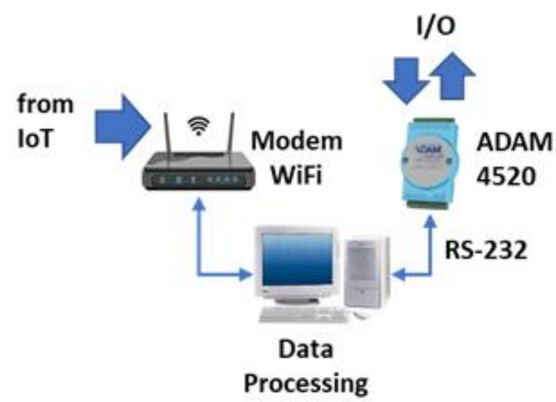

Fig. 4. Data processing PC unit configuration.

Fig. 4 shows the configuration of the Data Processing PC unit; the PC is connected to the ADAM-4520 via RS-232, and the ADAM-4017 and ADAM-4068 are connected to the ADAM-4520 via RS-485. The Data Processing unit runs the Logic Control application program to select the treatment method (Time-Based or Rule-Based). The result of processing sensor data using the Logic Control method is a decision related to actuator activity.

2) Control panel: The control panel in this study serves as a hardware integration hub that connects the actuators to the data processing PC, ensuring that the sensing–decision–actuation process runs smoothly[37]. The Control Panel consists of: 1) Input Module (ADAM 4017) [16]: receives data from analog sensors, 2) Output Module (ADAM 4068): sends control signals to the actuator to activate the irrigation pump. The I/O (Input/Output) modules on the PAC are modular (hot-swappable), meaning they can be added or removed, providing flexibility for system expansion. The ADAM-4520 is an isolated serial converter that converts RS-232 communication to RS-422/RS-485 for greater noise immunity and transmission ranges of up to approximately 1.2 km, while protecting the host computer via 3000 VDC isolation. Fig. 5 shows the connection between the I/O module and the PC.

The ADAM-4068 is an 8-channel relay-based digital output module designed to control field devices such as pumps, valves, or alarms via RS-485 commands (ASCII/Modbus RTU). Meanwhile, the ADAM-4017 is an 8-channel analog input module that reads analog sensor signals (voltage/current), converts them into 16-bit digital data that can be processed by a control system, and also supports Modbus RTU communication. Communication between ADAM modules occurs via a fieldbus; ADAM modules are fundamentally designed to operate within a "master-slave" architecture. The master (typically a PC) is responsible for initiating all communication with other components [38]. I/O modules (such as the ADAM-4017 or ADAM-4068) act as slaves that only respond to requests from the master.

ADAM modules use an RS-485 physical interface for inter-module communication. This network topology allows for multi-drop or daisy-chain connections, enabling dozens of modules to be connected on a single pair of cables [39]. This is highly efficient for connecting numerous sensors and actuators spread across agricultural areas. The protocol used for communication between ADAM modules and the master can be: 1) Modbus/RTU, the most widely used standard industrial protocol. The master sends a Modbus "command" (e.g., "read the analog input value from module ID 01") and the ADAM module responds with the requested data; 2) ASCII Command, which uses simple ASCII-based text commands. Often, a PC only has a standard RS-232 port (an older serial port), so the ADAM 4520 functions as a bridge or translator, converting the RS-232 signal from the PC into an RS-485 signal.

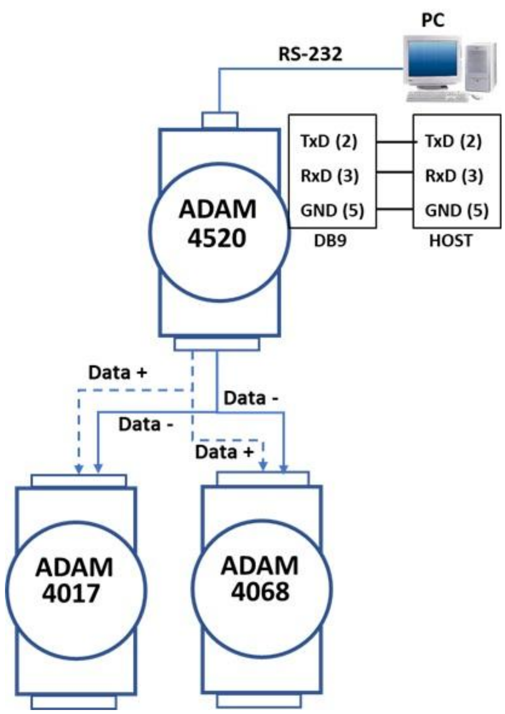

Fig. 5. Wiring diagram on the control panel.

3) Actuator: Actuators serve as execution components that translate control decisions from the PC into physical actions in the fertigation process. Based on readings from pH, EC, and growing medium humidity sensors, as well as time-based (routine schedule) and rule-based (correction upon deviation) control logic, actuators control devices such as pumps and/or valves to deliver water and nutrient solutions as needed. Thus, the actuator serves as a direct link between data processing results and actual field conditions, while ensuring that water or nutrient delivery is timely, measured, and responsive to changes in growing medium conditions.

The PC sends low-voltage control signals via the I/O module. These signals trigger the actuators to operate. In the context of a fertigation system, this relationship is clearly evident: 1) The PC makes a decision, and the actuator acts: The PC executes rule-based logic that states, "If soil moisture is below 60%, activate irrigation in Zone A." The PC then sends the appropriate electrical signal; 2) The Role of Relays and Solenoid Valves: the signal is received by the output module (such as the ADAM-4068, which contains relays). The relay functions as an intermediate switch to activate actuators requiring higher power, such as water pumps or solenoid valves; 3) Execution of Crop Treatment: the solenoid valve opens, allowing water and nutrient solution to flow into the root zone. The water pump turns on, creating the required pressure. It is the physical action of opening the valve or turning on the pump that is performed by the actuator; Fig. 6 shows the actuator design.

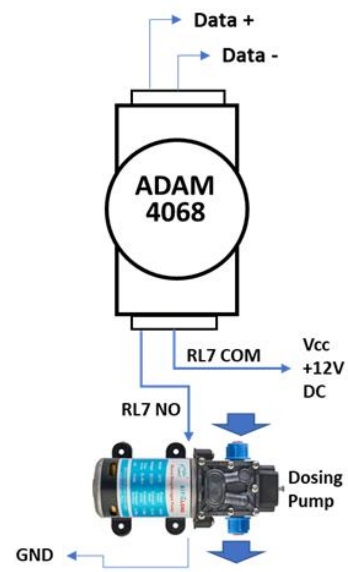

Fig. 6. Actuator wiring diagram (ADAM 4068 to dosing pump).

Data+ and Data- are the RS-485 communication lines connecting the ADAM 4068 [16] to the PC (via the ADAM 4520); these lines are used to receive control instructions from the host. RL7 COM (Common) is the common terminal of channel 7 relay on the ADAM 4068. This pin serves as the power supply input (+12V DC) for the actuator. RL7 NO (Normally Open) is the normally open terminal on channel 7 of the relay. When the relay is inactive, the circuit between COM and NO is open. When the relay is activated by the PC, the circuit closes, allowing the +12V DC voltage to flow to the dosing pump. Vcc +12V DC is the positive power supply voltage (+12 volts) used to operate the dosing pump. It is routed through the RL7 COM line and passed to RL7 NO when the relay is active. GND is the ground line connected to the negative side of the power supply and the dosing pump, thereby forming a complete electrical circuit [40]. With this configuration, the dosing pump will only turn on when the relay on channel RL7 is activated. This allows the PC, via the ADAM 4068, to automatically control nutrient delivery based on calculations from data analysis. The data processing PC is the decision-maker, and the actuators are the physical executors that ensure crop management proceeds in accordance with the programmed automation strategy; without the actuators, the intelligent decisions made by the data processing PC would never be translated into actual actions in the field.

4) Monitoring of growing media: In this context, the PAC (PC Data Processing Unit) receives growing medium data from a WSN (Wireless Sensor Network)-based sensor network [17]. Data from the WSN is transmitted directly to the PC Data Processing Unit via a WiFi (wireless) network. In this study, the configuration between the WSN and the PC utilizes the Fog Computing concept [18], thereby eliminating the need for a cloud server.

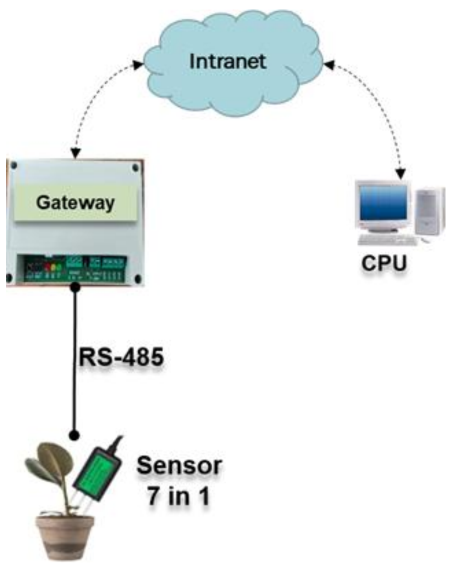

Fig. 7. WSN configuration as a data source.

The growing medium sensors and the Gateway (as shown in Fig. 7) are WSN devices that continuously measure EC, pH, and humidity parameters in the growing medium. The data collected by the gateway is then sent to the PC Data Processing unit using the MQTT (Message Queuing Telemetry Transport) protocol [19]. Data is collected periodically (e.g., every 10 minutes). This interval ensures that the PAC always has up-to-date information on plant conditions without overloading the network.

The PAC uses the received data to apply rule-based treatments as follows: 1) "If-Then" Conditional Logic: Data received from the WSN (e.g., humidity = 55%, pH = 6.0) is used to evaluate pre-programmed rules; 2) Automatic Decision-Making: The PAC makes real-time decisions based on this data; example rules: (a) "IF humidity < 60% THEN activate the irrigation pump," (b) "IF pH > 6.5 THEN apply an acid solution to stabilize the growing medium"; 3) The fertigation control system does not provide nutrients based on a schedule, but only reacts when actual field conditions require intervention, ensuring efficient use of resources. This study emphasizes the importance of integrating real-time data from sensors in decision-making regarding plant nutrient application.

5) Sensor plant health and productivity indicators: The pH, EC (Electrical Conductivity), and growing medium moisture content are key indicators in precision agriculture that provide fundamental information regarding nutrient availability and uptake by plants; these three parameters serve as early indicators of nutrient requirements [12] [20] [21]. pH (Acidity Level) measures the acidity or alkalinity of the growing medium. It is not an indicator of the amount of nutrients present, but rather an indicator of their availability. As an indicator, this means that nutrients are absorbed most effectively within a specific pH range. Most plants prefer a pH between 5.5 and 6.5. For example, if the pH is too high (alkaline), nutrients such as Iron (Fe), Manganese (Mn), and Phosphorus (P) will be locked within the growing medium and cannot be absorbed by the roots, even if they are present in sufficient quantities. Initial Action: A suboptimal pH reading is an early indicator that the plant is at risk of nutrient deficiency in the future, so adjusting the pH of the nutrient solution is necessary.

EC (Electrical Conductivity) measures the total concentration of dissolved salt ions in the growing medium solution; these salts constitute the fertilizer (nutrients). As an indicator, EC directly reflects the concentration of the nutrient solution available in the root zone. For example, a low EC value indicates that the growing medium is deficient in nutrients and the plants need to be fertilized. Conversely, if the EC value is too high, it indicates an excess of fertilizer, which risks causing toxicity or nutrient burn (burnt roots). Initial Action: Monitoring EC can provide a direct indication of whether the current nutrient dose is appropriate or needs to be increased or decreased.

The moisture content of the growing medium indicates the amount of water available within it. As an indicator, this means that water serves as the medium for nutrient transport. Nutrients must be dissolved in water so that they can be absorbed by the roots through osmosis and transpiration. Example: If the growing medium is too dry, nutrient uptake will cease entirely, even if the pH and EC values are ideal. A drastic drop in moisture levels indicates the need for immediate irrigation, which is often combined with nutrient application (fertigation) to maintain a steady flow of nutrients to the plants.

Fig. 8. (7-in-1) Growing medium sensor for a fertigation control system.

The sensor used in this study is the RS485-based Multisensor Digital soil sensor [22], specifically designed for precision agriculture applications and fertigation systems, as shown in Fig. 8. This sensor serves as a digital sensing device that is a critical component of modern agricultural systems; it is a detector that integrates the ability to measure several key growing medium parameters simultaneously, often including moisture, temperature, electrical conductivity (EC), and pH.

Table II shows the role of growing medium parameters as indicators of plant health and productivity.

TABLE II. PLANT HEALTH AND PRODUCTIVITY INDICATORS

Parameter Monitoring	Description	Action
EC (Electrical Conductivity)	An EC level that is too high or too low can hinder plant growth and overall health.	• If the EC reading is too high, add clean water (without nutrients).• If the EC reading is too low, add a nutrient solution with a higher concentration, adjusted according to the plant's growth stage (early stage, vegetative stage, or generative/flowering/fruiting stage).
pH (potential of hydrogen)	The primary effect of pH on plants is on nutrient availability. Suboptimal pH levels prevent nutrients from being bound and absorbed by the plants, even though they are present in the growing medium.	• Optimal nutrient availability occurs at a growing medium pH of 5.5–7.0.• If the growing medium pH is too low (< 5.5), the pH must be adjusted toward neutral.• If the growing medium pH is too high (> 7.0), corrective measures are needed to lower the pH.
Moisture Content of the Growing Medium	Adequate water availability in the growing medium is essential for plant survival, but too much or too little water can have negative effects.	• Add water and/or nutrients according to the moisture level of the growing medium.

By monitoring these three key indicators in real time—humidity to ensure nutrient transport occurs, pH to ensure nutrients are accessible and available, and EC to ensure nutrient concentrations are sufficient but not excessive—the fertigation control system can automatically adjust the necessary treatments to maintain optimal root zone conditions for plant growth. WSN sensors provide accurate, real-time data to the PAC, enabling it to implement rule-based treatments so that plants receive optimal growing conditions.

6) Design of the system logic control application program: In the context of PAC functionality, the PC (Data Processing) contains the Logic Control and HMI application programs. Logic Control is an application program that functions as the Decision Layer [36]. The Decision Layer is a component of the layered architecture responsible for high-level decision-making, such as interpreting sensor data, selecting or planning actions, and then sending commands to the execution/actuation layer below it. The Decision Layer also encompasses decision-making and planning processes, which generate a sequence of actions. Meanwhile, the HMI (Human-Machine Interface) is a feature that provides a dashboard for users (farmers) to operate and monitor fertigation activities. Fig. 9 shows a Flow Diagram of how the HMI application program works.

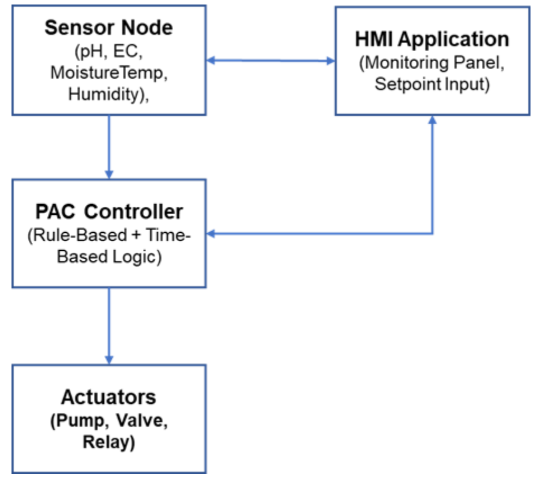

Fig. 9. Flowchart of the HMI application program's operation.

The Sensor Node measures environmental conditions and plant nutrition based on pH, EC, and growing medium moisture parameters. The PC serves as the logic control center with two main control methods: 1) Time-Based Logic, which activates the pump at specific times; 2) Rule-Based Logic, which activates the pump if the growing medium sensor detects specific conditions (e.g., low EC). The HMI provides a user interface to view real-time data, set time points, limit parameters, or perform manual overrides. Actuators receive signals from the PC to activate pumps, valves, or relays according to the plant's growth stage or sensor conditions.

The relationship between the logic controller and the HMI can be described as follows: 1) The logic controller is an application program containing rules regarding plant care, such as the following instruction [26]: "IF the humidity sensor reads below 60% AND the sun is shining brightly, THEN activate the pump for 5 minutes." Logic control translates human ideas (research findings) into machine language that can be executed by the PAC [27]; 2) The HMI is the "face" of the control system [29]; it is not used to create new logic, but to monitor and interact with the existing Logic Control.[30].

In this study, the PAC does not rely on an internet connection, thereby reducing the potential for disruptions caused by network instability. Additionally, since the PAC is PC-based, the development of application programs and the human-machine interface (HMI) becomes more flexible and robust. The PAC allows programming using high-level programming languages, enabling the system to be designed with more complex, dynamic features that are easily adaptable to user needs and the desired level of control complexity. [31].

One of the activities in this study was to develop an HMI model (as a dashboard) with several features, including: 1) Hardware Settings, 2) Time-Based "treatment" features, 3) Rule-Based "treatment" features, to support the operation of the fertigation control system [33]. These two treatment features are required simultaneously, as not all plant conditions can be predicted solely from sensor data or growth stages alone. By combining both, the fertigation control system becomes more flexible [32], responsive, and precise. Table III illustrates the design concepts of time-based and rule-based "treatment."

TABLE III. THE DESIGN CONCEPT OF "TREATMENT"

Features / Approach	Time-Based Treatment	Rule-Based Processing
Main Trigger	A fixed schedule (for example, every day at 7 a.m.)	Actual field conditions (If humidity < X%)
Basis for the Decision	The time specified by the "User."	Programmed "If-Then" Logic
Data Source	System clock/calendar	Real-time sensors (humidity, temperature, etc.)
Flexibility	Not weather-resistant	Flexible (adapting to changing conditions)
Response	Procedural (following a set of steps)	Reactive (responds to the sensor threshold)
Complexity	Low (simple timer)	Medium (requires sensors and logic)
Application Examples	Standard home garden irrigation	Automated greenhouse irrigation system

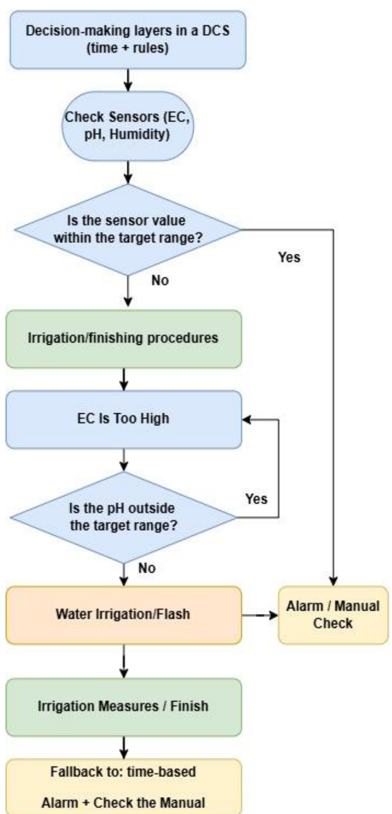

Fig. 10. Flowchart of plant treatment (time-based and rule-based).

Fig. 10 shows a flowchart of the logic control in the DCS for time- and rule-based plant treatment control (base schedule + correction rules). Based on this flowchart, the workflow of the fertigation control system [34] is as follows: 1) The system reads the sensors, 2) monitors whether the growing medium parameters are still within normal limits, 3) In rule-based mode, the system evaluates deviation conditions, 4) If a disturbance occurs (e.g., sensor/communication issues), the system falls back to time-based mode and continues to run the minimum schedule while issuing an alarm to suggest a manual check. Moreover, Table IV shows the features for hardware settings, which include: port connectivity, output control [35], data acquisition, measurement calibration, data storage, and logging.

TABLE IV. HARDWARE SETUP AND SYSTEM CONFIGURATION

Category: Setting	Job Function / Job Description	Software Implementation / HMI	Information Regarding ADAM Hardware
Port Connectivity	Open/Close the Serial Communication Port	The "Connect" / "Disconnect" button on the HMI. A drop-down menu for selecting the COM port (e.g., COM1, COM2) and setting the baud rate (e.g., 9600 bps).	Using the ADAM-4520 as a converter and RS-485 bus.
Output Control (Relay)	Trying to run the relays (RL0–RL7)	The HMI displays 8 toggle switches labeled "Pump A," "Valve 1," etc. Each relay has a visual status indicator (ON/OFF light).	Send a Modbus/ASCII Write command to the ADAM-4068 to enable or disable a specific relay.
Data Acquisition	Trying to Retrieve Data from the Sensor	The "Refresh Data" button or automatic update on the HMI that displays sensor values in real time (for example, "Humidity: 75%").	Send a Modbus/ASCII Read command to the ADAM-4017 to read 8 analog input channels and receive data from IoT sensors.
Measurement Calibration	Calibration of Sensor Measurement Results	The configuration menu on the HMI for entering offset and scaling values (for example, converting a raw 4–20 mA value to 0–100% humidity).	Adjust the digital reading of the ADAM-4017 to match the actual physical value.
Data Storage & Logs	Save Settings and Record Relay Usage (RL0–RL7)	The "Save Settings" button on the HMI. An automatic data logging feature that runs in the background.	The data log is stored in a text file (.txt) or database on the PC/PAC, recording when the ADAM-4068 relay turns on and off.

C. Development: HMI and Decision Layer Treatment Programming

Pseudocode-1 shows the pseudocode for the system initialization application program, which includes: general initialization and communication port status initialization.

Pseudocode-1

```
// Initialize global variables and data structures
DEFINE current_moisture, current_ph, current_ec AS FLOAT
DEFINE pump_status, valve_A_status AS BOOLEAN
DEFINE scheduled_time_A, scheduled_duration_A AS TIME/DURATION
DEFINE rule_moisture_threshold AS FLOAT

// Initialize communication port status
```

```
SET comm_port_open = FALSE

FUNCTION InitializeSystem()
    LOAD_SETTINGS_FROM_FILE("conFig. txt")
    DISPLAY("System initialized. Awaiting connection.")
END FUNCTION
```

Fig. 11 shows the HMI display as the system begins the initialization process. The growing medium sensor will display the current data.

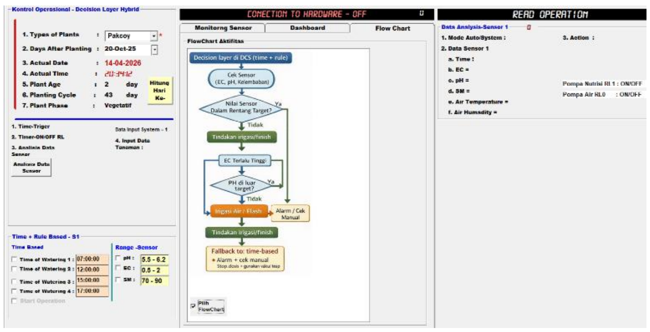

Fig. 11. HMI screen during system initialization.

Moreover, Pseudocode 2 shows the pseudocode for the application program to configure port communication, manually test the relay, and calibrate the sensor. These functions can be accessed by the user through the programming interface or the HMI configuration menu.

Pseudocode-2

```
// Use Case: Configure Communication Port
FUNCTION ConfigurePort(port_name, baud_rate)
IF comm_port_open THEN
CLOSE_PORT()
END IF
OPEN_PORT(port_name, baud_rate)
IF success THEN
SET comm_port_open = TRUE
DISPLAY("Port " + port_name + " opened successfully.")
SAVE_SETTINGS_TO_FILE("conFig. txt")
ELSE
DISPLAY("Failed to open port. Check connection.")
END IF
END FUNCTION

// Use Case: Test Relay Function (ADAM 4068)
FUNCTION TestRelay(relay_id, duration_seconds)
IF comm_port_open THEN
DISPLAY("Testing Relay R" + relay_id + " for " + duration_seconds + "s")
SEND_MODBUS_WRITE(ADAM_4068_ADDRESS, relay_id, STATE_ON)
LOG_ACTION("RL" + relay_id + " turned ON for test")
WAIT(duration_seconds * 1000 milliseconds)
SEND_MODBUS_WRITE(ADAM_4068_ADDRESS, relay_id, STATE_OFF)
LOG_ACTION("RL" + relay_id + " turned OFF after test")
ELSE
DISPLAY("Error: Port not open. Cannot test hardware.")
END IF
END FUNCTION

// Use Case: Retrieve Data from Sensor (ADAM 4017) and Calibrate
FUNCTION ReadAndCalibrateSensorData()
IF comm_port_open THEN
// 1. Retrieve raw data
raw_moisture_data = SEND_MODBUS_READ(ADAM_4017_ADDRESS, CHANNEL_0)
raw_ph_data = SEND_MODBUS_READ(ADAM_4017_ADDRESS, CHANNEL_1)

// 2. Apply calibration (scaling/offset)
current_moisture = APPLY_CALIBRATION(raw_moisture_data, MOIST_SCALE, MOIST_OFFSET)
current_ph = APPLY_CALIBRATION(raw_ph_data, PH_SCALE, PH_OFFSET)

DISPLAY("Moisture: " + current_moisture + "%, pH: " + current_ph)
SAVE_SETTINGS_TO_FILE("conFig. txt") // Saves calibration settings
END IF
END FUNCTION

// Use Case: Save Settings and Record Usage (Log File)
FUNCTION LogAction(action_description)
timestamp = GET_CURRENT_TIMESTAMP()
APPEND_TO_FILE("usage_log.txt", timestamp + " - " + action_description + NEWLINE)
END FUNCTION
```

Fig. 12 shows the HMI Hardware Settings screen. This HMI interface is designed to provide intuitive yet powerful control, with high flexibility in setting critical fertigation parameters locally via the PAC. The system can be used to support decision-making based on the actual conditions of the growing medium.

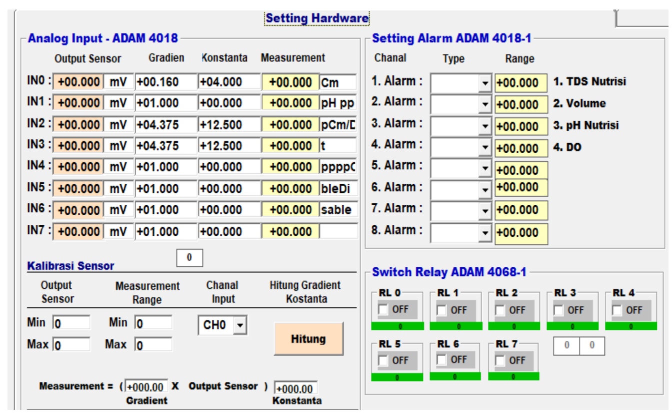

Fig. 12. Hardware settings dashboard.

Pseudocode 3 shows the pseudocode for time-based treatment; this logic runs continuously in the main system loop.

Pseudocode-3

```
FUNCTION RunTimeBasedTreatment()
current_time = GET_CURRENT_TIME()

// Check if the current time matches the scheduled start time
IF current_time IS scheduled_time_A THEN
DISPLAY("Executing Time-Based Treatment A")

// Activate pump/valve (e.g., Relay 0 on ADAM 4068)
SEND_MODBUS_WRITE(ADAM_4068_ADDRESS, RELAY_0, STATE_ON)
LogAction("RL0 ON - Start time treatment")

// Wait for the scheduled duration
WAIT(scheduled_duration_A)

// Deactivate pump/valve
SEND_MODBUS_WRITE(ADAM_4068_ADDRESS, RELAY_0, STATE_OFF)
LogAction("RL0 OFF - End time treatment")
END IF
END FUNCTION
```

Moreover, Pseudocode-4 shows the pseudocode for rule-based treatment. This logic runs continuously in a loop within the main system and typically checks environmental conditions more frequently than time-based systems.

Pseudocode-4

```
FUNCTION RunRuleBasedTreatment()
   // First, update sensor data to get current conditions
   ReadAndCalibrateSensorData()

   // Apply the 'If-Then' rule
   IF current_moisture < rule_moisture_threshold THEN
      // Condition met: Soil is too dry. Need to irrigate.
      DISPLAY("Rule Triggered: Moisture below threshold. Starting irrigation.")

      // Activate pump/valve (e.g., Relay 1 on ADAM 4068)
      SEND_MODBUS_WRITE(ADAM_4068_ADDRESS, RELAY_1, STATE_ON)
      LogAction("RL1 ON - Rule based irrigation started")

      // Continue irrigation until the threshold is met again
      WHILE current_moisture < (rule_moisture_threshold + 5) // Stop when 5% above threshold
         WAIT(60000) // Wait 1 minute before checking moisture again
         ReadAndCalibrateSensorData()
      END WHILE

      SEND_MODBUS_WRITE(ADAM_4068_ADDRESS, RELAY_1, STATE_OFF)
      LogAction("RL1 OFF - Rule based irrigation finished")
   ELSE
      DISPLAY("Rule Check: Moisture is OK. No action needed.")
   END IF
END FUNCTION
```

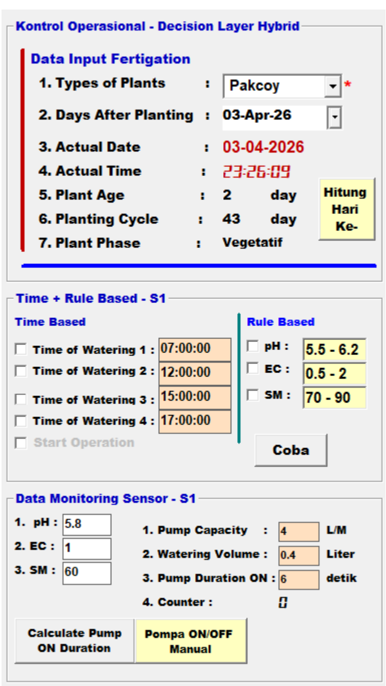

Fig. 13. HMI interface for control and monitoring.

Fig. 13 shows the HMI interface for configuring and using time- and rule-based treatment logic controls. The treatment HMI provides four time-setting inputs, as well as settings for three indicator parameters: EC, pH, and growing medium humidity. Monitoring data is available to track the condition of the growing medium in real time.

III. Result and Discussion

This chapter presents testing methods focused on three application programs: hardware configuration, HMI, and the integration of time-based treatment with rule-based treatment. The objective of the testing is to ensure that the developed application programs not only function as designed but are also sufficiently reliable to support measured fertigation operations that can be easily monitored by users via the HMI. The evaluation method is conducted through three approaches: 1) hardware testing to assess the functional performance of the developed PAC-based fertigation prototype, focusing on sensor and actuator operation, power stability, and data communication reliability; 2) functional testing (Black -Box Testing) was used to verify the functions of the HMI and control modules without examining the program's internal structure, but rather based on the consistency of input–output and the system's response to test scenarios; 3) performance testing based on acceptance criteria was applied to assess key technical parameters, such as response latency, actuator response time, and communication success, to ensure they meet the established thresholds.

A. Hardware Functional Testing

TABLE V. Preliminary Field Testing Hardware

No.	Test item	Threshold	Results (measured)	Unit	Status
1	Sensor Functionality (deviation)	≤ 5.0	2.5	%	Pass
2	Actuator Function (response time)	< 2.0	1.2	s	Pass
3	Power Consumption (current deviation)	≤ 3.0	2.0	A	Pass
4	Voltage Stability (range)	11.4–12.6	12.1	V	Pass
5	Reliability (continuous operation)	≥ 72.0	96.0	h	Pass
6	Sensor Calibration (deviation)	≤ 3.0	2.8	%	Pass
7	Communication Interface (success rate)	≥ 99.0	99.5	%	Pass
8	System Response (latency)	< 500.0	320.0	ms	Pass
9	Thermal (Temperature)	25.0–30.0	27.0	°C	Pass
10	Thermal (Humidity)	50.0–70.0	60.0	%RH	Pass

Table V shows the hardware testing conducted to evaluate the functional performance of the developed PAC-based fertigation prototype, focusing on sensor and actuator operation, power stability, communication reliability, and basic environmental resilience. Table V defines acceptance thresholds for each hardware test item and summarizes the initial test results by comparing the measured values (results) against the acceptance thresholds/criteria (thresholds) referenced in Table V. Each test point is given a "Pass" status if the result meets the established criteria (e.g., maximum deviation limit, minimum reliability duration, or permissible operating range for temperature and humidity).

TABLE VI. BLACK-BOX TESTING OF HMI FUNCTIONS

No	Test Case (TC)	Feature	Test step (scenario)	Metric (measurable)	Threshold	Result (measured)	Unit	Trials (n)	Status (Pass/Fail)	Remarks
1	TC-1	Open serial port (valid)	Enter valid COM (1–10) → Connect	Connection time	≤ 5	2	s	10	Pass	No issues observed
2	TC-2	Open serial port (invalid)	Enter invalid COM (1–10) → Connect	Error display time	≤ 2	1	s	10	Pass	No issues observed
3	TC-3	Relay output test	Toggle RL0–RL7 ON/OFF	Relay response time	≤ 500	300	ms	10	Pass	No issues observed
4	TC-4	Analog input/sensor read	Click "Read data."	Data refresh time	≤ 1000	500	ms	10	Pass	No issues observed
5	TC-5	Select treatment method	Select Time-Based / Rule-Based	Menu load time	≤ 500	500	ms	10	Pass	No issues observed
6	TC-6	Run plant treatment	Run Time/Rule-Based execution	Execution latency	≤ 1000	500	ms	10	Pass	No issues observed

Moreover, Fig. 14 demonstrates the stable and reliable performance of the PAC, as it successfully met the predetermined system performance criteria. Basic functional tests (Nos. 1 and 2) showed that all input and output components functioned as intended. The calibration test (No. 6) is a critical aspect in ensuring data accuracy. By comparing the WSN sensor measurement results against standard reference values (using a Portable TDS and pH/EC standards), the system showed low measurement deviation, namely ≤ ±3%, indicating high accuracy for the intended application. The system's electrical aspects were tested via the Power Consumption Test (No. 3) and Voltage Stability Test (No. 4). Test results demonstrate good power efficiency; total power consumption remains within the adapter's capacity, and no excessive current surges occur. Additionally, the power supply proved stable during operation, with minimal voltage drop and ripple (deviation <3% from nominal), ensuring a safe operating environment for electronic components. Long-term performance and system response testing also yielded positive results.

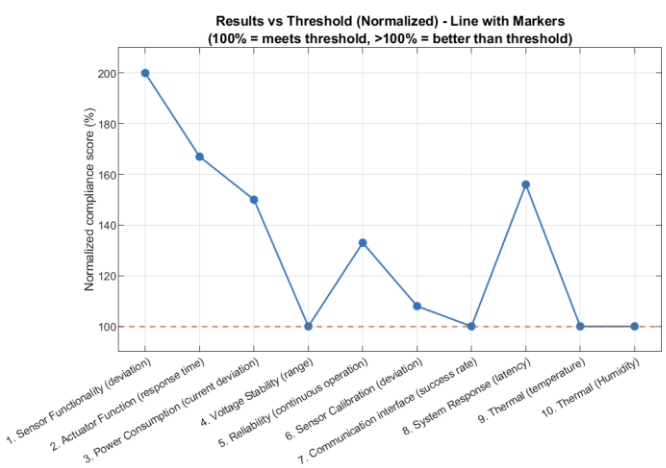

Fig. 14. Graph of PAC hardware test results.

Fig. 14 shows a comparison of normalized Results vs. Threshold, where the 100% reference line indicates that the system meets the minimum acceptance criteria. Values above 100% indicate performance that exceeds the threshold. Overall, the prototype meets the specified functional requirements, confirming that the hardware subsystem is sufficiently stable for initial field testing and subsequent integration with time-based and rule-based control functions.

Hardware connection testing (ADAM 4068 and ADAM 4017) via the serial port yielded positive and robust results (TC-1, TC-2). The hardware control module functions properly, facilitating smooth user interaction with sensors and actuators (TC-3, TC-4). Testing of the application's navigation menu and main control logic was also completed (TC-5, TC-6). This black-box testing confirms that the application program has met its primary functionality requirements, ranging from hardware connectivity (ADAM Modules) and I/O control (relays and sensors) to menu navigation and the execution of automatic control logic, thereby deeming the application stable. Fig. 15 shows the results of the Black-Box test in Table VI in the form of a normalized compliance score calculated using Eq. (1).

$$(\text{Threshold} / \text{Result}) \times 100 \quad (1)$$

B. *Black-Box Testing of HMI and Programming Interface*

The next testing phase involves conducting functional testing using the black-box testing method on the HMI application program. Black-box testing is a software testing method that does not examine the internal structure of the code or program.

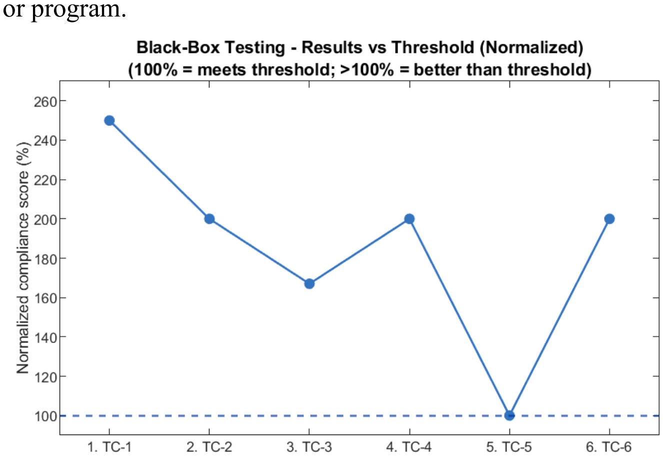

Fig. 15. Graph of the black box HMI test results.

The dashed line at 100% indicates the minimum pass threshold (the result is exactly equal to the threshold). Values above 100% indicate performance that exceeds the criteria because the measured response time/latency is less than the threshold. In the graph, all test cases are ≥ 100%, so all HMI functions are marked as Pass. The highest score appears in TC-1 (≈250%) because the connection time is much faster than the threshold (2 s vs. 5 s), while TC-5 is exactly at 100% because the menu loading time is equal to the threshold (500 ms), making it the point that is closest to the limit and can be prioritized for optimization if necessary.

C. Simulation of Treatment Integration Function Testing (Time-Based and Rule-Based)

Time-based control serves as a baseline control to maintain a consistent supply of nutrients and water as long as pH, EC, and humidity remain within normal limits. When these parameters deviate, indicating a nutrient or water deficiency or excess, the system switches to rule-based control for more specific actions: low EC triggers nutrient addition, while excessively high EC triggers dilution or flushing with clean water.

Table VII shows how control decisions adjust sensor conditions, so that the time-based and rule-based approaches complement each other. Table VII also shows the simulation tests conducted as follows: under normal operating conditions, as seen in the data for Day 1 (08:00) and Day 15 (16:00), the system executes routine protocols. Although temperature and humidity fluctuate during the day, the system maintains the plant's status in the healthy (optimal) category because the pH and EC parameters remain within tolerance limits. This demonstrates the effectiveness of standard nutrient scheduling when the environment is stable. However, the advantage of rule-based control becomes evident when the system encounters anomalies. On Day 5 (14:00), the system detected a drop in EC to 1.1 mS/cm and pH to 5.5. The system automatically triggered the 'Add Nutrient A' treatment to correct the nutrient deficiency. Conversely, on Day 10 (09:00), when a risk of high salinity (EC 2.5 mS/cm) was detected, the system took emergency action in the form of a 'Clean Water Flush' to reduce excess mineral salts. This integration demonstrates that the application program not only operates based on time but also possesses situational intelligence to maintain plant health through targeted interventions based on real-time sensor data.

The threshold values in Table VII are based on the optimal ranges commonly used for leafy vegetables (e.g., lettuce, bok choy, arugula) in hydroponic/soilless culture systems. For pH, the range of 5.5–6.5 is widely recommended because it maintains optimal nutrient availability in the nutrient solution [23]. For EC, leafy vegetables generally fall within a range of approximately 1.2–2.0 mS/cm (for example, lettuce is often reported to be stable within a range of about 1.2–1.8 mS/cm, and studies on lettuce have also evaluated EC up to 2.0 mS/cm) [23]. Meanwhile, moisture in soilless growing media is more accurately expressed as substrate volumetric water content (VWC); studies on leafy vegetables such as arugula evaluated VWC at 0.20–0.50 $m^3 \cdot m^{-3}$ and showed that maintaining VWC around 0.30 $m^3 \cdot m^{-3}$ supports water use efficiency while maintaining growth and quality [24][25]. Therefore, in the simulation in Table VII, a practical range of 30–50% VWC is used as the operating range (threshold) to represent safe substrate moisture conditions for leafy vegetables in soilless systems. Fig. 16 shows pH, EC, and substrate moisture after normalization to their ideal ranges (0% = lower limit, 100% = upper limit). Occurrences outside the threshold indicate values approaching 0% or 100%, triggering rule-based corrective actions, while values within the range indicate stable conditions under time-based scheduling. Based on the functional testing simulations conducted, it was found that the application is capable of adaptively transitioning control from a time-based approach to a rule-based approach in accordance with the dynamics of the growing medium.

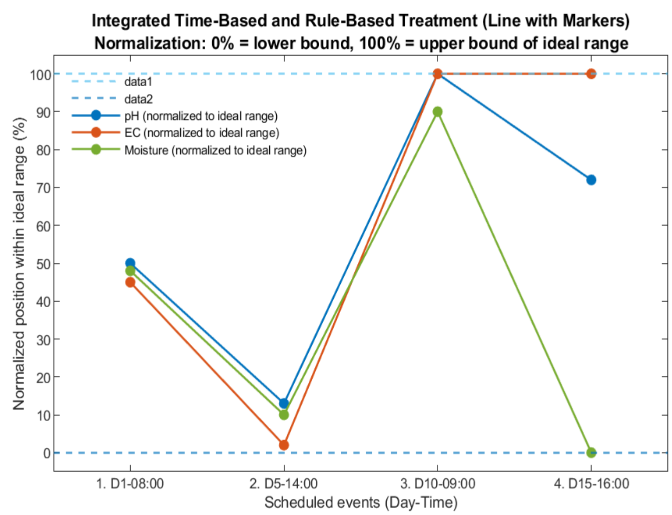

Fig. 16. Results of the simulation of the integration function test across treatments.

TABLE VII. SIMULATION OF INTEGRATION FUNCTIONALITY TESTING ACROSS TREATMENTS (TIME-BASED AND RULE-BASED)

Day	Time	pH	pH threshold	EC (mS/cm)	EC threshold (mS/cm)	Moisture *(%VWC)	Moisture threshold (%VWC)	Control mode	Trigger condition	Action executed
1	08:00	6.1	5.5–6.5	1.6	1.2–2.0	40	30–50	Time-based	Within thresholds	Scheduled dosing executed
5	14:00	5.4	5.5–6.5	1.0	1.2–2.0	32	30–50	Rule-based	pH low & EC low	Increase nutrient concentration / adjust pH up
10	09:00	6.7	5.5–6.5	2.3	1.2–2.0	48	30–50	Rule-based	pH high & EC high	Dilute/flush with water; adjust pH down
15	16:00	6.2	5.5–6.5	1.8	1.2–2.0	28	30–50	Rule-based	Moisture low	Irrigation pulse to restore moisture

*VWC = Volumetric Water Content

*EC = Electrical Conductivity

IV. Discussion

The results of the hardware application program testing (Table V) and the functional testing using the Black Box method on the HMI (Table VI) indicate that all major subsystems (sensor data acquisition, actuation, communication, and interface) meet the acceptance criteria. The system latency of 320 ms and the actuator response time of 1.2 s are well below the dynamic range of the fertigation process, which typically occurs on the order of seconds to minutes; thus, computational delay is not a primary limiting factor in this prototype. Conversely, reading accuracy and communication stability are the most critical aspects because they determine decisions at the pH/EC/humidity thresholds. In the Black Box testing for the HMI application program, the system met the primary operational requirements (connectivity, I/O control, sensor readings, menu navigation, and treatment execution) with margins generally >100%; the optimization priority lies with TC-5, as it is right at the threshold (500 ms).

In the testing, the integration of time-based and rule-based controls provides two layers of regulation; the time-based control ensures the continuous supply of nutrients and water, while the rule-based control acts as a corrective measure when deviations occur. This approach is relevant for cultivating leafy vegetables such as pak choi and lettuce, which are sensitive to changes in EC and growing medium moisture. Due to the hysteresis/persistence in the rule-based system, the system can avoid excessive action caused by momentary fluctuations, thereby potentially maintaining more stable growing medium conditions and reducing water and nutrient waste.

However, this study is still limited to functional validation at the preliminary field testing stage, so it has not yet evaluated the agronomic impacts (e.g., growth, yield, or water/nutrient use efficiency) over a full cultivation cycle.

V. Conclusion

This study successfully developed a precision fertigation control system based on a Programmable Automation Controller (PAC) that integrates time-based and rule-based controls within a single data-driven architecture. The system is capable of automatically regulating water and nutrient delivery based on a routine schedule and the actual conditions of the growing medium, as measured by pH, EC, and humidity sensors. Test results indicate that the time-based approach is effective in maintaining nutrient supply stability, while the rule-based approach is more adaptive in handling environmental anomalies in real-time. The integration of both approaches yields a system that is more flexible, precise, and efficient compared to microcontroller-based IoT systems. This system has the potential to support the implementation of precision agriculture and Industry 4.0 technologies in the agricultural sector, particularly in the sustainable management of fertigation for horticultural crops. As a further development, the integration of predictive algorithms or machine learning could be considered to enhance the system's ability to make more adaptive and proactive decisions.

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