JOURNAL LA MULTIAPP

VOL. 07, ISSUE 04 (874-890), 2026
DOI: 10.37899/journallamultiapp.v7i4.5234

Design and Implementation of a Multi-Zone Automatic Irrigation Control System Based on Sugeno Fuzzy Logic for a Melon Seedling Incubator

Ahmad Fauzan[1], Reni Rahmadewi[1]

[1]*Electrical Engineering Study Program, Faculty of Engineering, Universitas Singaperbangsa Karawang, Indonesia*

**Corresponding Author: Ahmad Fauzan*
E-mail: 2210621160024@student.unsika.ac.id

Article Info

Article history:
Received 20 July 2026
Received in revised form 2 September 2026
Accepted 20 September 2026

Keywords:
Capacitive Moisture Sensor
Irrigation Control
Melon Seedling
Normalized Moisture Index
Sugeno Fuzzy Logic

Abstract

Maintaining appropriate moisture conditions is important for the early growth of melon seedlings. This study developed a zone-based irrigation control system using six capacitive moisture sensors, an Arduino Mega 2560, one water pump, and three solenoid valves. The six seedling trays were divided into three irrigation zones, with the lower value of two sensors used to represent each zone condition. Each sensor was calibrated individually, and the analog readings were converted into a dimensionless Normalized Moisture Index (NMI). A zero-order Sugeno fuzzy inference system was used to determine irrigation duration based on four input conditions: Very Dry, Dry, Moist, and Wet. Lower NMI values produced longer irrigation durations, while wet conditions produced no irrigation command. The developed system was able to process sensor readings, calculate zone conditions, generate irrigation-duration outputs, and control the pump and solenoid valves according to the designed logic. The system demonstrates the application of capacitive sensing and Sugeno fuzzy control for irrigation management in melon seedlings.

Introduction

The agricultural sector plays an important role in fulfilling food demands and supporting economic development. In horticultural cultivation, the seedling stage is one of the most critical phases because the quality and uniformity of seedlings significantly influence plant growth and productivity in the following cultivation stages. Therefore, maintaining suitable environmental conditions during the seedling stage is essential to support healthy and uniform seedling development (Grossnickle & Ivetić, 2022; Sripathy & Groot, 2023 Dadlani et al., 2023). Cocopeat is commonly used as a growing medium for seedling cultivation due to its high water retention capability, good aeration properties, and favorable characteristics for root growth (Narkhede et al., 2025; Abdullah et al., 2026; Thakur & Garg, 2024; Wu et al., 2025). However, the moisture condition of cocopeat must be maintained within an appropriate range because insufficient moisture can cause water stress and inhibit seedling growth, while excessive moisture may reduce oxygen availability around the roots and potentially increase the risk of root-related diseases (Akhter et al., 2026; Lim et al., 2025; Liu et al., 2026; Zampieri et al., 2023).

Based on observations conducted at a commercial seedling cultivation facility, the irrigation process is still performed manually by applying water at fixed time intervals. The watering process is carried out approximately every 2 to 2.5 hours, resulting in around twelve irrigation cycles per day. This method requires continuous human involvement and may cause

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

inconsistent moisture distribution due to variations in human estimation and changing environmental conditions (Liu et al., 2023; Rasheed et al., 2022; Taheri et al., 2025). Consequently, some seedling trays may experience insufficient moisture, while others may receive excessive irrigation. A conventional time-based irrigation approach does not consider the actual moisture condition of the growing medium. The moisture level can continuously change due to plant water absorption, evaporation, and environmental temperature. Therefore, an automatic irrigation control system capable of monitoring the actual moisture condition of the growing medium is required to provide a more efficient and adaptive irrigation process (Bwambale et al., 2022; Ramakrishnan et al., 2024; Nsoh et al., 2024; Liu et al., 2025).

Capacitive soil moisture sensors can be utilized to monitor the moisture condition of the cocopeat medium in real time (Aziz et al., 2025; Suganthakrishna et al., 2025; Helmy et al., 2025; Abdelmoneim et al., 2025). In a multi-zone seedling system, different trays may have different moisture conditions because of variations in water distribution, evaporation rates, and plant water uptake. Therefore, the irrigation system should be able to evaluate the moisture condition of each irrigation zone independently and determine the appropriate amount of water required for each zone. To provide adaptive irrigation decisions, an intelligent control method is required. Compared to conventional threshold-based control, fuzzy logic can handle gradual changes in moisture conditions and provide a more flexible irrigation response (Liu et al., 2025; Madu et al., 2026; Pahlawan et al., 2025). The Sugeno fuzzy logic method is suitable for irrigation applications because it converts the measured moisture condition into a precise output in the form of irrigation duration based on predefined fuzzy rules.

Besides moisture control, environmental temperature also influences seedling conditions. High temperatures can increase the evaporation rate of the growing medium and affect the surrounding environment of the seedlings (Costa et al., 2023; Liang et al., 2025; Yusuf et al., 2025; Al-Shammary et al., 2025; Thenveettil et al., 2024). Therefore, a supporting temperature regulation mechanism using a temperature sensor and an exhaust fan can be implemented to maintain a suitable temperature condition. This temperature control is performed using a conventional ON/OFF method due to the simple operational characteristic of the exhaust fan. Furthermore, local monitoring of system operation is necessary to allow users to observe the current system condition directly. A liquid crystal display (LCD) can be used to provide real-time information regarding moisture conditions, irrigation operation, temperature readings, and actuator status without requiring additional external devices (Borankulova et al., 2025; Lan et al., 2023; Han et al., 2022; Morchid et al., 2024) .

Based on these considerations, this research proposes the design and implementation of a multi-zone automatic irrigation control system based on Sugeno fuzzy logic for a seedling incubator. The system utilizes multiple capacitive soil moisture sensors to monitor the moisture condition of each tray, processes the data using a microcontroller to determine irrigation duration, controls the irrigation actuator automatically, provides supporting temperature regulation through an exhaust fan, and displays system information through a local monitoring interface.

Methods

Research Methodology

This study employed an experimental method to design, implement, and evaluate an automatic multi-zone irrigation control system based on Sugeno fuzzy logic. The system integrates capacitive soil moisture sensors, an Arduino Mega 2560, and a Sugeno fuzzy controller to determine irrigation duration for each zone. A DHT22 sensor and an exhaust fan provide temperature regulation, while an LCD displays system information. The research stages included literature review and requirement analysis, hardware and software design,

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

sensor calibration, Sugeno fuzzy controller development, system implementation, and performance evaluation.

Data Collection Method

Data were collected through three methods. Literature study reviewed journals, books, and technical documents on automatic irrigation, soil moisture sensing, fuzzy logic, Arduino systems, and environmental monitoring. Observation was conducted to analyze the characteristics of fermented cocopeat and determine irrigation requirements. Experimentation was performed for sensor calibration, controller development, hardware integration, and system testing to evaluate the performance of the proposed irrigation system.

System Overview

The proposed system automatically monitors the moisture of fermented cocopeat and determines irrigation duration using Sugeno fuzzy logic. Six capacitive soil moisture sensors monitor six planting trays grouped into three irrigation zones, with the lowest moisture value in each zone representing irrigation needs. An Arduino Mega 2560 processes sensor data, executes fuzzy inference, and controls a water pump and solenoid valves via relay modules. A DHT22 sensor regulates an exhaust fan based on temperature, while a 20×4 LCD provides real-time monitoring of system conditions.

Software Design

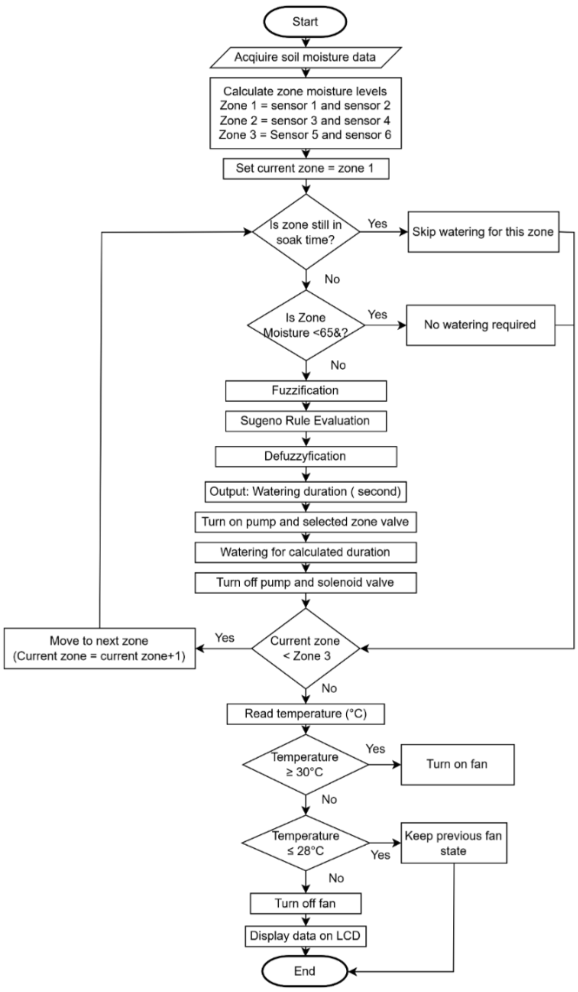

Figure 1. Irrigation Control System Software Flowchart

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

The software was developed using the Arduino IDE and implemented on the Arduino Mega 2560. It acquires sensor data, converts ADC readings into Normalized Moisture Index (NMI) values, performs Sugeno fuzzy inference, controls irrigation and temperature regulation, and updates the LCD. The program initializes all components, groups six moisture readings into three irrigation zones, selects the minimum moisture value for each zone, determines irrigation duration through fuzzy logic, activates the pump and solenoid valves, applies a soaking period after irrigation, and controls the exhaust fan based on DHT22 temperature readings.

Hardware Design

The hardware consists of sensing devices, a processing unit, irrigation actuators, environmental control components, and a monitoring interface. The Arduino Mega 2560 functions as the main controller, while six Capacitive Soil Moisture Sensor V2.0 modules measure soil moisture. A DHT22 sensor monitors temperature, and irrigation is performed using a DC water pump and three solenoid valves controlled through relay modules. A 20×4 LCD displays moisture values, temperature, irrigation status, and fan operation for local monitoring.

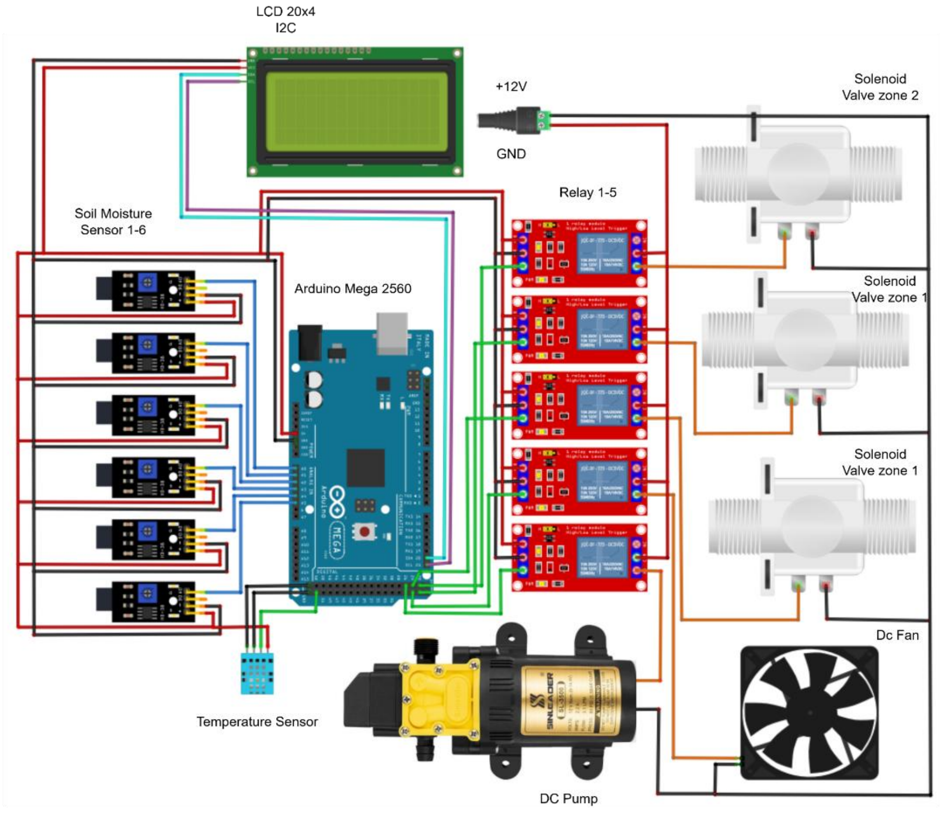

Figure 2. Hardware Design of the Irrigation Control System

Fuzzy Design of Irrigation Control System

The irrigation control subsystem utilizes the Sugeno fuzzy inference method to determine the watering duration based on the moisture condition of each irrigation zone. Sugeno fuzzy logic was selected because it produces a direct numerical output that can be used as the activation time of irrigation actuators. Unlike the Mamdani method, which requires an additional defuzzification process to obtain a crisp output, the Sugeno method calculates the final output using a weighted average of predefined singleton values. This characteristic makes the Sugeno method suitable for implementation on microcontroller-based systems with limited computational resources.

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

In the developed irrigation control system, the fuzzy controller does not only determine whether irrigation should be activated, but also calculates the appropriate watering duration according to the dryness level of the growing medium. This approach allows the system to perform gradual irrigation control, where drier growing media receive longer watering durations while wetter media receive shorter watering durations or no irrigation at all.

Results and Discussion

Actuator Testing

Each actuator was tested individually by sending an ON command from the Arduino Mega 2560 through the relay module. During each test, the actuator remained activated for 5 s before an OFF command was issued. The procedure was repeated three times for every actuator to evaluate the consistency of its switching behavior and operational stability. The expected response was then compared with the actual physical response. A test was considered successful when the actuator activated immediately after the ON command, remained stable throughout the 5 s activation period, and deactivated correctly after receiving the OFF command without abnormal behavior or switching failure.

Table 1. Actuator Testimg Result

No	Actuator	Relay Pin	Duration (s)	Expected Response	Actual Response	Result
1	Solenoid Valve Zone 1	D22	5	Valve opens	Valve opened	Passed
2	Solenoid Valve Zone 1	D22	5	Valve opens	Valve opened	Passed
3	Solenoid Valve Zone 1	D22	5	Valve opens	Valve opened	Passed
4	Solenoid Valve Zone 2	D24	5	Valve opens	Valve opened	Passed
5	Solenoid Valve Zone 2	D24	5	Valve opens	Valve opened	Passed
6	Solenoid Valve Zone 2	D24	5	Valve opens	Valve opened	Passed
7	Solenoid Valve Zone 3	D26	5	Valve opens	Valve opened	Passed
8	Solenoid Valve Zone 3	D26	5	Valve opens	Valve opened	Passed
9	Solenoid Valve Zone 3	D26	5	Valve opens	Valve opened	Passed
10	DC Pump	D28	5	Pump activates	Pump activated	Passed
11	DC Pump	D28	5	Pump activates	Pump activated	Passed
12	DC Pump	D28	5	Pump activates	Pump activated	Passed
13	DC Fan	D30	5	Fan rotates	Fan rotated	Passed
14	DC Fan	D30	5	Fan rotates	Fan rotated	Passed
15	DC Fan	D30	5	Fan rotates	Fan rotated	Passed

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

Based on Table 1, shows that all actuators responded correctly to the control commands generated by the Arduino Mega 2560 during the functional verification. The three solenoid valves successfully completed the opening and closing sequence, while the DC pump and DC fan operated continuously throughout the 5 s activation period and deactivated properly after the OFF command. The actuator responses remained consistent across all three repetitions, with no delayed switching, operational interruption, or abnormal behavior observed.

The successful results confirm that the relay-based actuator subsystem is capable of reliably executing the control commands issued by the microcontroller. Since all actuators exhibited stable and consistent operation during repeated testing, the subsystem was considered suitable for integration with the sensor monitoring and fuzzy-based irrigation control algorithm. This verification ensures that any subsequent irrigation decisions generated by the control algorithm can be translated into reliable physical actions by the irrigation system.

Mist Sprinkler Duration Response Test

The Sugeno fuzzy irrigation control test The mist sprinkler duration response test was conducted to determine the most appropriate mist activation duration for each moisture condition used as the singleton output of the Sugeno fuzzy controller. The evaluation was performed by observing the moisture response of the cocopeat medium after irrigation. The measured parameters included the initial Normalized Moisture Index (NMI), final NMI after irrigation, and the corresponding NMI increase (ΔNMI).

Three fuzzy moisture conditions were evaluated, namely Moist, Dry, and Very Dry. For each condition, three candidate mist activation durations were tested. The Moist condition was evaluated using 3 s, 4 s, and 5 s, the Dry condition using 5 s, 6 s, and 7 s, and the Very Dry condition using 8 s, 9 s, and 10 s. The final NMI was then compared with the desired operating moisture range of 60–70%. A duration was considered suitable when it increased the moisture level into the target range without exceeding the overwatering threshold of 75%.

Table 2. Mist Sprinkler Duration Response Results

No	Initial Condition	Initial NMI (%)	Duration (s)	Final NMI (%)	ΔNMI (%)	Evaluation
1	Moist	60.2	3	63.5	3.3	Below optimum
2	Moist	59.8	4	65.2	5.4	Acceptable
3	Moist	60.0	5	67.1	7.1	Selected
4	Dry	50.6	5	58.5	7.9	Below target
5	Dry	49.8	6	61.7	11.9	Acceptable
6	Dry	48.9	7	66.0	17.1	Selected
7	Very Dry	39.6	8	57.2	17.6	Below target
8	Very Dry	37.4	9	62.3	24.9	Acceptable
9	Very Dry	35.8	10	68.4	32.6	Selected

Table 3. Fuzzy Output Duration Selection Based on Mist Sprinkler Response

Fuzzy Condition	Tested Duration (s)	Evaluation Basis	Selected Duration (s)
Moist	3, 4, 5	The 5 s duration produced the final NMI closest to the middle of the target moisture range (60–70%) without causing overwatering.	5
Dry	5, 6, 7	The 7 s duration provided the most effective moisture correction and	7

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

		consistently reached the target moisture range.	
Very Dry	8, 9, 10	The 10 s duration generated the highest moisture increase while maintaining the final NMI below the overwatering threshold of 75%.	10
Wet	0	No irrigation was required because the moisture level was already within the desired range.	0

The results presented in Table 3 indicate that longer mist activation durations generally produced greater increases in the moisture level of the cocopeat medium. However, the required irrigation duration depended on the initial moisture condition. Media classified as Moist required only a small moisture correction, whereas Dry and Very Dry conditions required progressively longer irrigation durations to reach the target operating range.

For the Moist condition, the 3 s and 4 s durations increased the NMI but produced values closer to the lower boundary of the target range. The 5 s duration resulted in a final NMI of 67.3%, representing the most suitable moisture level without approaching the overwatering threshold.

For the Dry condition, a 5 s duration was insufficient because the final NMI remained below 60%. Increasing the duration to 6 s successfully reached the target range, while 7 s produced a final NMI of 66.1%, which was closer to the desired operating condition.

For the Very Dry condition, the 8 s duration did not provide sufficient moisture recovery. Although the 9 s duration reached the target range, the 10 s duration produced a final NMI of 68.5%, which was closer to the desired operating range while remaining safely below the overwatering limit of 75%. Based on these results, the singleton outputs of the Sugeno fuzzy controller were defined as 0 s (Wet), 5 s (Moist), 7 s (Dry), and 10 s (Very Dry). These durations provided the most appropriate moisture correction for each fuzzy condition while maintaining the final moisture level within the desired operating range.

Sugeno Fuzzy Irrigation Control Testing

The Sugeno fuzzy irrigation control test was conducted to verify whether the fuzzy logic controller produced a consistent irrigation-duration output based on the Normalized Moisture Index (NMI) input. This test focused on the mathematical response of the zero-order Sugeno fuzzy controller, not on the physical moisture increase produced by irrigation.

The singleton output durations used in this verification were determined based on the mist sprinkler duration-response experiment presented in the previous section. The experimental results indicated that activation durations of 10 s, 7 s, and 5 s provided the most suitable moisture correction for the Very Dry, Dry, and Moist conditions, respectively, while the Wet condition required no irrigation (0 s). These experimentally selected durations were then implemented as the singleton outputs of the zero-order Sugeno fuzzy controller.

The final irrigation duration is calculated using:

$$\left[t = \frac{\sum_{i=1}^{n} w_i \, z_i}{\sum_{i=1}^{n} w_i}\right]$$

where t is the final irrigation duration, w_i is the firing strength of Rule i, $z_i$is the singleton output of Rule i, and n is the number of fuzzy rules.

The test was conducted using 30 NMI input values covering Very Dry, Dry, Moist, transition, and Wet conditions. These input values were used to verify whether the fuzzy controller

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

produced a gradual and consistent output response across the full operating range of the irrigation control system

Table 4. Sugeno Fuzzy Logic Verification Results

No	NMI Input (%)	Dominant Condition	Expected Output Behavior	Controller Output (s)	Result
1	0,0	Very Dry	Long irrigation duration	10,00	Passed
2	5,0	Very Dry	Long irrigation duration	10,00	Passed
3	100	Very Dry	Long irrigation duration	10,00	Passed
4	15,0	Very Dry	Long irrigation duration	10,00	Passed
5	20,0	Very Dry	Long irrigation duration	10,00	Passed
6	25,0	Very Dry	Long irrigation duration	10,00	Passed
7	30,0	Very Dry	Long irrigation duration	10,00	Passed
8	32,5	Very Dry	Long irrigation duration	10,00	Passed
9	35,0	Very Dry / Dry transition	Decreasing irrigation duration	10,00	Passed
10	37,5	Very Dry / Dry transition	Decreasing irrigation duration	9,25	Passed
11	40,0	Very Dry / Dry transition	Decreasing irrigation duration	8,50	Passed
12	42,5	Very Dry / Dry transition	Decreasing irrigation duration	7,75	Passed
13	45,0	Dry transition	Medium irrigation duration	7,00	Passed
14	47,5	Dry	Medium irrigation duration	7,00	Passed
15	50,0	Dry	Medium irrigation duration	7,00	Passed
16	52,5	Dry	Medium irrigation duration	7,00	Passed
17	55,0	Dry / Moist transition	Decreasing irrigation duration	7,00	Passed
18	57,5	Dry / Moist transition	Decreasing irrigation duration	6.20	Passed
19	60,0	Moist	Short irrigation duration	5.67	Passed
20	62,5	Moist	Short irrigation duration	5.29	Passed
21	65,0	Moist / Wet transition	Very short irrigation duration	5.00	Passed
22	67,5	Moist / Wet transition	Very short irrigation duration	2,86	Passed

ISSN: 2716-3865 (Print), 2721-1290 (Online)

Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

No	NMI Input (%)	Dominant Condition	Expected Output Behavior	Controller Output (s)	Result
23	70,0	Wet transition	Near-zero irrigation duration	0.00	Passed
24	72,5	Wet	No irrigation or near-zero output	0.00	Passed
25	75,0	Wet	No irrigation	0.00	Passed
26	80,0	Wet	No irrigation	0.00	Passed
27	85,0	Wet	No irrigation	0.00	Passed
28	90,0	Wet	No irrigation	0.00	Passed
29	95,0	Wet	No irrigation	0.00	Passed
30	100,0	Wet	No irrigation	0.00	Passed

Table 4 demonstrates that the implemented Sugeno fuzzy controller generated irrigation durations consistent with the designed membership functions and experimentally selected singleton outputs. Low NMI values (0–32.5%) consistently produced the maximum irrigation duration of 10 s, corresponding to the Very Dry condition. Within the transition region between Very Dry and Dry, the controller output gradually decreased from 10.00 s to 7.75 s through weighted-average defuzzification. Likewise, the transition from Dry to Moist produced a gradual reduction from 7.00 s to 5.29 s, while the transition toward Wet further reduced the irrigation duration to 2.86 s before reaching 0 s once the NMI entered the Wet region. This smooth output variation confirms that the implemented Sugeno inference mechanism successfully avoided abrupt changes in irrigation duration, resulting in stable control behavior suitable for automatic irrigation applications.

Integrated System Testing

The integrated irrigation control test consisted of four groups of verification scenarios: single-zone operation, priority zone selection, fuzzy membership transition, and sequential irrigation. These scenarios were designed to verify the complete control chain, including zone NMI determination, fuzzy inference, priority-based zone selection, actuator activation, and sequential irrigation using the implemented soaking-time mechanism.

$$NMI_{zone} = min(NMI_{tray1}, NMI_{tray2})$$

The calculated zone NMI is then processed by the Sugeno fuzzy controller. The singleton output durations used in this test were obtained from the mist sprinkler duration-response experiment and implemented as the final singleton values of the Sugeno fuzzy controller, namely 10 s for Very Dry, 7 s for Dry, 5 s for Moist, and 0 s for Wet.

The integrated verification scenarios are divided into four categories. The first category evaluates single-zone operation to verify that each irrigation zone can independently perform fuzzy inference and actuator control. The second category evaluates the priority selection algorithm by providing multiple irrigation requests simultaneously to verify that the controller always selects the zone with the lowest NMI. The third category verifies the fuzzy membership transition by testing NMI values located within the overlapping regions of adjacent membership functions. Finally, the sequential irrigation category verifies the implemented state machine and soaking-time mechanism, ensuring that multiple irrigation requests are executed sequentially according to the irrigation priority rather than simultaneously.

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

Table 5. Integrated Irrigation Control System Verification Results

No	Test Scenario	Z1 NMI (%)	Z2 NMI (%)	Z3 NMI (%)	Selected Zone	Calculated Fuzzy Duration (s)	Observed System Response
1	Zone 1 – Very Dry	28.63	69.42	72.15	Zone 1	10.00	Pump and Valve 1 were activated for 10 s.
2	Zone 2 – Very Dry	71.08	33.57	68.91	Zone 2	10.00	Pump and Valve 2 were activated for 10 s.
3	Zone 3 – Very Dry	69.84	72.33	31.46	Zone 3	10.00	Pump and Valve 3 were activated for 10 s.
4	Zone 1 – Dry	47.82	70.63	73.25	Zone 1	7.00	Pump and Valve 1 were activated for 7 s.
5	Zone 2 – Dry	71.24	49.53	69.61	Zone 2	7.00	Pump and Valve 2 were activated for 7 s.
6	Zone 3 – Dry	70.41	72.18	48.74	Zone 3	7.00	Pump and Valve 3 were activated for 7 s.
7	Zone 1 – Moist	61.47	71.86	74.03	Zone 1	5.43	Pump and Valve 1 were activated for 5.43 s.
8	Zone 2 – Moist	72.55	62.14	70.38	Zone 2	5.33	Pump and Valve 2 were activated for 5.33 s.
9	Zone 3 – Moist	71.69	72.84	60.88	Zone 3	5.52	Pump and Valve 3 were activated for 5.52 s.
10	Priority Selection (Z1 Dry, Z2 Very Dry)	48.26	34.12	69.88	Zone 2	10.00	Zone 2 was selected because it had the lowest NMI.
11	Priority Selection (Z1 Very Dry, Z2 Dry)	32.71	47.96	70.84	Zone 1	10.00	Zone 1 was selected because it had the lowest NMI.
12	Priority Selection (Z2 Moist, Z3 Very Dry)	71.55	60.93	30.74	Zone 3	10.00	Zone 3 was selected because it had the lowest NMI.
13	Priority Selection (All Dry)	48.94	46.85	49.73	Zone 2	7.00	The controller selected the minimum NMI among three dry zones.

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

No	Test Scenario	Z1 NMI (%)	Z2 NMI (%)	Z3 NMI (%)	Selected Zone	Calculated Fuzzy Duration (s)	Observed System Response
14	Priority Selection (All Very Dry)	33.84	29.91	31.46	Zone 2	10.00	The controller selected the minimum NMI among three very dry zones.
15	Membership Verification (Very Dry–Dry Boundary)	43.62	69.43	73.81	Zone 1	7.41	The calculated duration changed smoothly from the Very Dry singleton toward the Dry singleton.
16	Membership Verification (Dry–Moist Boundary)	56.48	70.56	74.38	Zone 1	6.48	The controller generated an intermediate irrigation duration during the Dry–Moist transition.
17	Membership Verification (Moist–Wet Transition)	68.46	73.27	76.35	Zone 1	1.86	The controller produced a near-zero irrigation duration approaching the Wet membership.
18	Sequential Irrigation Verification (Two Zones)	31.84	48.92	78.54	Zone 1 → Zone 2	10.00 → 7.00	Zone 1 was irrigated first. After the soaking period expired, the controller continued irrigation to Zone 2, while Zone 3 was skipped because it was already Wet.
19	Sequential Irrigation Verification (Two Zones)	74.36	33.71	49.45	Zone 2 → Zone 3	10.00 → 7.00	Zone 2 was irrigated first, followed by Zone 3 after the soaking period. Zone 1 remained inactive.
20	Sequential Irrigation Verification (Three Zones)	47.95	30.83	60.71	Zone 2 → Zone 1 → Zone 3	10.00 → 7.00 → 5.55	The controller completed sequential irrigation according to the priority algorithm and soaking mechanism until all irrigation

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

No	Test Scenario	Z1 NMI (%)	Z2 NMI (%)	Z3 NMI (%)	Selected Zone	Calculated Fuzzy Duration (s)	Observed System Response
							requests were fulfilled.

Table 5 demonstrates that the integrated irrigation control system operated according to the implemented control algorithm. The controller successfully determined the zone NMI using the minimum NMI value from each irrigation zone, selected the irrigation zone with the lowest moisture level, calculated the irrigation duration using the Sugeno fuzzy inference method, and executed the corresponding actuator commands. The verification also confirmed smooth fuzzy output transitions across the overlapping membership regions and validated the priority-based sequential irrigation mechanism implemented through the soaking-time state machine. When multiple zones simultaneously required irrigation, the controller consistently irrigated the driest zone first, temporarily excluded the irrigated zone during the soaking period, and subsequently continued irrigation to the remaining zones after the soaking period had elapsed. These results demonstrate that the complete irrigation control chain—from sensor acquisition and NMI calculation to fuzzy inference, irrigation scheduling, and actuator execution—operated as intended.

Besides verifying the irrigation control subsystem, the integrated system verification also evaluated the temperature monitoring and cooling subsystem. This test was conducted to verify whether the DHT22 sensor readings were correctly processed by the controller and whether the cooling fan responded according to the predefined temperature threshold. Unlike the irrigation subsystem, which employs Sugeno fuzzy logic to determine irrigation duration, the cooling subsystem operates using a threshold-based control strategy. Therefore, several representative ambient temperature conditions corresponding to typical daily environmental variations were selected to verify the fan activation and deactivation responses. The verification results are presented in Table 6.

Table 6. Temperature Monitoring and Cooling Fan Verification Results

No	Scenario	DHT22 Reading (°C)	Fan Command	Observed Response	Result
1	Morning Condition	25.1	OFF	Fan remained OFF	Passed
2	Late Morning Condition	28.6	OFF	Fan remained OFF	Passed
3	Noon Condition	30.4	ON	Fan started immediately	Passed
4	Hot Afternoon Condition	32.1	ON	Fan operated continuously	Passed
5	Cooling Transition	29.8	OFF	Fan stopped automatically	Passed
6	Evening Condition	28.4	OFF	Fan remained OFF	Passed

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

Table 6 shows that the temperature monitoring and cooling subsystem operated according to the implemented control logic. During the morning, late morning, and evening conditions, the measured temperature remained below the predefined activation threshold, causing the cooling fan to remain OFF. When the chamber temperature increased during the noon and hot afternoon conditions, the controller successfully activated the cooling fan. During the cooling transition scenario, the fan was automatically deactivated after the measured temperature dropped below the threshold. These results demonstrate that the DHT22 sensor, control algorithm, and cooling fan operated as an integrated subsystem, providing reliable temperature monitoring and automatic cooling within the MELOWS chamber.

Overall System Analysis

The overall system evaluation was conducted to assess the performance of the developed irrigation control system after integrating the soil moisture sensing subsystem, Sugeno fuzzy irrigation controller, irrigation hardware, temperature control subsystem, and LCD monitoring subsystem.

The calibration results demonstrated that all capacitive soil moisture sensors exhibited strong linear relationships between ADC readings and normalized moisture values, with coefficients of determination exceeding 0.94. These calibration equations enabled the conversion of raw sensor readings into moisture percentages suitable for irrigation control applications, and confirmend by the soil moisture sensor verification test (Pramanik et al., 2022; Ebstu et al., 2026). Similarly, the DHT22 sensor verification confirmed its reliability for environmental monitoring, showing high precision and sufficient accuracy to govern the cooling subsystem based on predefined temperature thresholds.

Functional testing of the actuators demonstrated that the solenoid valves, DC pump, and cooling fan operated consistently without switching failures. This confirmed the reliability of the relay module interface in executing microcontroller commands under real operational conditions. The mist sprinkler duration response test successfully identified the optimal irrigation durations10 s for Very Dry, 7 s for Dry, 5 s for Moist, and 0 s for Wet to return the cocopeat media to the 60–70% target moisture range without causing overwatering. These empirically determined durations were successfully implemented as singleton outputs in the Sugeno fuzzy controller. Furthermore, the verification of the fuzzy logic proved that the controller produced smooth, non-increasing output transitions across the operational NMI range, avoiding abrupt changes in irrigation behavior.

The integrated system testing validated the complete control chain. The controller effectively determined the representative zone NMI using the minimum value approach and accurately executed the Sugeno fuzzy rules. Crucially, the multi-zone verification demonstrated the robustness of the system's priority and queueing algorithm. When multiple zones required irrigation simultaneously, the controller correctly prioritized the driest zone and executed the requests sequentially. This queueing mechanism, combined with the implemented soaking-time delay, ensures maximum water pressure is delivered to each zone independently while preventing excessive power draw that could disrupt the microcontroller. Finally, the temperature control subsystem successfully maintained the internal chamber environment by activating the exhaust fan when temperatures reached the 30 °C threshold and deactivating it upon cooling to 28 °C. Overall, the integrated results confirm that the MELOWS system successfully combined IoT monitoring, fuzzy-based irrigation, and environmental control to provide a stable, automated, and reliable incubator for melon seedling cultivation.

Conclusion

Based on the results of laboratory tests on twelve specimens, it can be concluded that plain rebar Ø10 mm and D10 mm threaded rebar have the same mechanical characteristics that are

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

adequate for use as reinforced concrete reinforcement, but with different advantages. In tensile testing, plain rebar obtained an average breaking strength of 516.33 MPa and a yield strength of 375.33 MPa, slightly higher than the threaded rebar which obtained 511.67 MPa and 360.00 MPa, while the proof strength values of both were practically equivalent at 360.67 MPa and 362.67 MPa. In the bending test, the bending strength of both materials was almost identical, namely 848.33 MPa and 848.00 MPa with a difference of only 0.04%, but the deformed rebar has a higher absorption energy, namely 43.15 Joules compared to 41.38 Joules, and all specimens were able to undergo bending without cracking or breaking with the coefficient of variation of all parameters below 5%. These findings indicate that the shape of the reinforcement surface does not have a major effect on tensile strength or flexural strength, but rather on the ability of plastic deformation, so for residential construction in Jakarta that must take into account earthquake loads, deformed rebar is still recommended as the main reinforcement because of its superior ductility and adhesion to concrete, while plain rebar can still be used in stirrups and ties according to applicable planning provisions..

Acknowledgment

The author would like to thank the Civil Engineering Study Program, Faculty of Engineering, Esa Unggul University for the academic support provided, as well as to the management and staff of the Civil Engineering Laboratory of Esa Unggul University for the facilities and technical assistance during the implementation of tensile testing and bending testing.

References

Abdelmoneim, A. A., Al Kalaany, C. M., Dragonetti, G., Derardja, B., & Khadra, R. (2025). Comparative analysis of soil moisture-and weather-based irrigation scheduling for drip-irrigated lettuce using low-cost internet of things capacitive sensors. *Sensors*, *25*(5), 1568. https://doi.org/10.3390/s25051568

Abdullah, U. H., Keumalasari, S., Yana, D., & Aufa, P. N. (2026). Correlation Analysis of Cocopeat Planting Media with Plant Height, Stem Diameter, and Number of Leaves of Oil Palm Plants (Elaeis guineensis Jacq). *Biotropika: Journal of Tropical Biology*, *14*(2), 154-160. https://doi.org/10.21776/ub.biotropika.2026.014.02.06

Akhter, T., Muzamil, M., Rashid, S., Bashir, A., Singh, H., Malik, S., & Banday, R. U. Z. (2026). Impact of Compaction on Soil Properties, Plant Growth and Yield Potential: A Critical Approach for Sustainable Crop Production System. *Transactions of the Indian National Academy of Engineering*, 1-14. https://doi.org/10.1007/s41403-026-00576-4

Al-Shammary, A. A. G., Al-Shihmani, L. S. S., Fernández-Gálvez, J., & Caballero-Calvo, A. (2025). A comprehensive review of impacts of soil management practices and climate adaptation strategies on soil thermal conductivity in agricultural soils. *Reviews in Environmental Science and Bio/Technology*, *24*(2), 513-543. https://doi.org/10.1007/s11157-025-09730-w

Aziz, A., Putratama, G. A., & Widiarto, W. (2025, December). Design and Implementation of an IoT-Driven Automatic Drip Irrigation and Fertilization System for Cocopeat-Based Greenhouse Farming. In *2025 9th International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE)* (pp. 353-357). IEEE. https://doi.org/10.1007/s40030-024-00857-7

Borankulova, G., Altybayev, G., Tungatarova, A., Yeraliyeva, B., Dulatbayeva, S., Murzakhmetov, A., & Bekbolatov, S. (2025). Development of real-time water-level monitoring system for agriculture. *Sensors*, *25*(17), 5564. https://doi.org/10.3390/s25175564

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agricultural Water Management*, *260*, 107324. https://doi.org/10.1016/j.agwat.2021.107324

Costa, J. M., Egipto, R., Aguiar, F. C., Marques, P., Nogales, A., & Madeira, M. (2023). The role of soil temperature in mediterranean vineyards in a climate change context. *Frontiers in Plant Science*, *14*, 1145137. https://doi.org/10.3389/fpls.2023.1145137

Dadlani, M., Gupta, A., Sinha, S. N., & Kavali, R. (2023). Seed storage and packaging. *Seed Science and Technology, Springer*, 239-266. https://doi.org/10.1007/978-981-19-5888-5_11

Ebstu, E. T., Hatiye, S. D., Goshime, D. W., Dingemanse, J. D., Dugassa, D. D., Fitensa, T., ... & Demeke, Y. G. (2026). Development and Testing of a Low-Cost Soil Moisture Sensor for Real-Time Irrigation Scheduling. *Irrigation and Drainage*, *75*(1), 173-187. https://doi.org/10.1002/ird.70026

Grossnickle, S. C., & Ivetić, V. (2022). Root system development and field establishment: effect of seedling quality. *New Forests*, *53*(6), 1021-1067. https://doi.org/10.1007/s11056-022-09916-y

Han, S., Kim, W., Lee, H. J., Joyce, R., & Lee, J. (2022). Continuous and real-time measurement of plant water potential using an AAO-based capacitive humidity sensor for irrigation control. *ACS Applied Electronic Materials*, *4*(12), 5922-5932. https://doi.org/10.1021/acsaelm.3c00060

Helmy, H. S., Abuarab, M. E., Abdeldaym, E. A., Abdelaziz, S. M., Abdelbaset, M. M., Dewedar, O. M., ... & Mokhtar, A. (2025). Field-grown lettuce production optimized through precision irrigation water management using soil moisture-based capacitance sensors and biodegradable soil mulching. *Irrigation Science*, *43*(5), 1045-1070. https://doi.org/10.1007/s00271-024-00969-9

Lan, R., Shen, W., Yao, W., Chen, J., Chen, X., & Yang, H. (2023). Bioinspired humidity-responsive liquid crystalline materials: from adaptive soft actuators to visualized sensors and detectors. *Materials Horizons*, *10*(8), 2824-2844. https://doi.org/10.1039/D3MH00392B

Liang, M., Chen, L., Chen, G., Zhao, Y., Liu, G., Sun, E., ... & Qu, P. (2025). Protective effects of straw mulching on soil health and function: a review. *Environmental Pollutants and Bioavailability*, *37*(1), 2533900. https://doi.org/10.1080/26395940.2025.2533900

Lim, J., Allen, K. S., Powning, C. B., & Harper, R. W. (2025). Impact of planting depth on urban tree health and survival. *Forests*, *16*(12), 1788. https://doi.org/10.3390/f16121788

Liu, X., Zhao, Z., & Rezaeipanah, A. (2025). Intelligent and automatic irrigation system based on internet of things using fuzzy control technology. *Scientific Reports*, *15*(1), 14577. https://doi.org/10.1038/s41598-025-98137-2

Liu, X., Zhao, Z., & Rezaeipanah, A. (2025). Intelligent and automatic irrigation system based on internet of things using fuzzy control technology. *Scientific Reports*, *15*(1), 14577. https://doi.org/10.1038/s41598-025-98137-2

Liu, Y., & Yang, Y. (2023). Spatial-temporal variability pattern of multi-depth soil moisture jointly driven by climatic and human factors in China. *Journal of Hydrology*, *619*, 129313. https://doi.org/10.1016/j.jhydrol.2023.129313

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

Liu, Y., Yang, Y., & Song, J. (2023). Variations in global soil moisture during the past decades: climate or human causes?. *Water Resources Research*, *59*(7), e2023WR034915. https://doi.org/10.1029/2023WR034915

Liu, Z., Li, Z., Wang, C., Tian, Y., Han, Q., Wan, X., ... & Liu, G. (2026). Morphological, physiological, and root metabolomic responses of Hemerocallis minor Mill. to drought stress. *Frontiers in Plant Science*, *17*, 1855949. https://doi.org/10.3389/fpls.2026.1855949

Madu, H., Yakubu, J., & Ahmad, U. (2026). A Mamdani Fuzzy Inference System for Intelligent Greenhouse Climate Control: Integrating Temperature, Humidity, and Soil Moisture for Adaptive Precision Agricultural Decision-Making. *Nigerian Journal of Operations Research*, *3*(3), 41-61. https://doi.org/10.67868/cvvkx809

Morchid, A., Jebabra, R., Alami, R. E., Charqi, M., & Boukili, B. (2024, May). Smart agriculture for sustainability: the implementation of smart irrigation using real-time embedded system technology. In *2024 4th International conference on innovative research in applied science, engineering and technology (IRASET)* (pp. 1-6). IEEE. https://doi.org/10.1109/IRASET60544.2024.10548972

Narkhede, H. I., Deokar, B. K., Kardile, D. S., Handore, A. V., & Surana, A. R. (2025). Cocopeat Biofilters: A sustainable approach for water purification and nutrient management. *Separation and Purification Technology*, *353*, 128558. https://doi.org/10.1016/j.seppur.2024.128558

Nsoh, B., Katimbo, A., Guo, H., Heeren, D. M., Nakabuye, H. N., Qiao, X., ... & Kiraga, S. (2024). Internet of things-based automated solutions utilizing machine learning for smart and real-time irrigation management: A review. *Sensors*, *24*(23), 7480. https://doi.org/10.3390/s24237480

Pahlawan, R., Nasution, B. B., & Fahmi, F. (2025, September). Soil Moisture Control Algorithm Using MQTT and Fuzzy Logic for Enhancing Agricultural Productivity. In *2025 International Conference on Computing and Applied Informatics (ICCAI)* (pp. 1-6). IEEE. https://doi.org/10.1109/ICCAI65301.2025.11278957

Pramanik, M., Khanna, M., Singh, M., Singh, D. K., Sudhishri, S., Bhatia, A., & Ranjan, R. (2022). Automation of soil moisture sensor-based basin irrigation system. *Smart Agricultural Technology*, *2*, 100032. https://doi.org/10.1016/j.atech.2021.100032

Ramakrishnan, T., Shameer, M. S., Prasath, A. M., Hemnath, R., Rathinam, S. C., & Avinasilingam, M. (2024, October). Automatic plant irrigation system. In *AIP Conference Proceedings* (Vol. 3221, No. 1, p. 030004). AIP Publishing LLC.

Rasheed, M. W., Tang, J., Sarwar, A., Shah, S., Saddique, N., Khan, M. U., ... & Sultan, M. (2022). Soil moisture measuring techniques and factors affecting the moisture dynamics: A comprehensive review. *Sustainability*, *14*(18), 11538. https://doi.org/10.3390/su141811538

Sripathy, K. V., & Groot, S. P. (2023). Seed development and maturation. In *Seed science and technology: Biology, production, quality* (pp. 17-38). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-5888-5_2

Suganthakrishna, S., Nirmala, R. G., Shreeram, S., & Sidharth, S. B. (2025, October). Development of a Low-Cost Capacitive Soil Moisture Monitoring System. In *2025 2nd International Conference on Artificial Intelligence and Knowledge Discovery in Concurrent Engineering (ICECONF)* (pp. 1-9). IEEE. https://doi.org/10.1109/ICECONF65644.2025.11379567

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0

Taheri, M., Bigdeli, M., Imanian, H., & Mohammadian, A. (2025). An overview of machine-learning methods for soil moisture estimation. *Water*, *17*(11), 1638. https://doi.org/10.3390/w17111638

Thakur, T., & Garg, A. (2024). Growth and flowering of ornamental pot plants influenced by growing media–A review. *Journal of Ornamental Horticulture*, *27*(2), 95-106. https://doi.org/10.5958/2249-880X.2024.00013.6

Thenveettil, N., Bheemanahalli, R., Reddy, K. N., Gao, W., & Reddy, K. R. (2024). Temperature and elevated CO2 alter soybean seed yield and quality, exhibiting transgenerational effects on seedling emergence and vigor. *Frontiers in plant science*, *15*, 1427086. https://doi.org/10.3389/fpls.2024.1427086

Wu, Y., Chen, R., Wang, F., Liu, X., & Chi, H. (2025). Enhanced Seedling Growth Effect of Cocopeat by Supplementation with Earthworm Manure as Nutrient Amendment. *Polish Journal of Environmental Studies*, *34*(4), 3853. https://doi.org/10.15244/pjoes/189294

Yusuf, A. G., Al-Yahya, F. A., Saleh, A. A., & Abdel-Ghany, A. M. (2025). Optimizing greenhouse microclimate for plant pathology: challenges and cooling solutions for pathogen control in arid regions. *Frontiers in Plant Science*, *16*, 1492760. https://doi.org/10.3389/fpls.2025.1492760

Zampieri, E., Pesenti, M., Nocito, F. F., Sacchi, G. A., & Valè, G. (2023). Rice responses to water limiting conditions: improving stress management by exploiting genetics and physiological processes. *Agriculture*, *13*(2), 464. https://doi.org/10.3390/agriculture13020464

ISSN: 2716-3865 (Print), 2721-1290 (Online)
Copyright © 2026, Journal La Multiapp, Under the license CC BY-SA 4.0