

An IoT-Enabled Ebb-and-Flow Cultivation System with Fan-Based Ventilation Control for *Bucephalandra* sp.

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Abstract. *Bucephalandra* is a high-value aquatic ornamental plant whose cultivation in tropical climates such as Lampung is constrained by ambient temperatures that frequently exceed its 22 to 28 degrees Celsius cultivation range. Most studies of network-connected control for plant environments address common horticultural crops, and the combination of ebb-and-flow subirrigation, closed-loop thermal control, and edge-node environmental monitoring on a single embedded platform has not been extensively reported for aquatic ornamental cultivation. This study designed and evaluated an integrated ebb-and-flow cultivation system for *Bucephalandra* built on an embedded microcontroller, combining proportional-integral-derivative fan ventilation control at a 26 degrees Celsius setpoint with scheduled flood-and-drain cycling and a dashboard hosted on an edge-computing node. After linear-regression calibration, the air temperature sensor achieved a mean absolute percentage error of 0.84 percent and a mean absolute error of 0.21 degrees Celsius, the humidity channel achieved 3.86 percent and 3.25 percent relative humidity, and the water temperature sensor achieved 0.78 percent and 0.21 degrees Celsius. Among four gain configurations tested, the setting with the lowest proportional gain produced a smooth, oscillation-free approach to the setpoint and was adopted for continued operation. The flood-and-drain schedule maintained timing within 1 to 2 seconds of the reference clock, and telemetry to a cloud spreadsheet achieved 99.4 percent packet storage success. Of the 218 seedlings placed in the system, 209 survived after one month (95.9 %), suggesting that the platform held conditions within the tolerable range for the species throughout the observation period. Temperature control, flood-drain timing, and IoT logging all performed within their design targets at laboratory scale.

Abstrak. *Bucephalandra* merupakan tanaman hias akuatik bernilai komersial tinggi yang budidayanya di iklim tropis seperti Lampung terkendala suhu lingkungan yang sering melampaui rentang fisiologis 22 hingga 28 derajat Celsius. Sebagian besar studi pengendalian lingkungan tanaman berbasis jaringan berfokus pada komoditas hortikultura umum, dan kombinasi irigasi ebb-and-flow, kendali termal closed-loop, serta pemantauan lingkungan berbasis edge node pada satu platform tertanam masih sangat terbatas dilaporkan untuk budidaya tanaman hias akuatik. Penelitian ini merancang dan mengevaluasi sistem budidaya ebb-and-flow terintegrasi untuk *Bucephalandra* yang dibangun pada mikrokontroler tertanam, memadukan kendali ventilasi kipas berbasis proporsional-integral-derivatif pada setpoint 26 derajat Celsius dengan penjadwalan siklus genang-surut serta dasbor pemantauan pada node komputasi tepi. Setelah kalibrasi regresi linear, sensor suhu udara mencapai galat persentase absolut rata-rata 0,84 persen dan galat absolut rata-rata 0,21 derajat Celsius, kanal kelembapan mencapai

3,86 persen dan 3,25 persen kelembapan relatif, dan sensor suhu air mencapai 0,78 persen dan 0,21 derajat Celsius. Di antara empat konfigurasi gain yang diuji, setelan dengan gain proporsional terendah menghasilkan respons menuju setpoint yang halus tanpa osilasi dan dipilih untuk operasi lanjutan. Siklus ebb-and-flow berjalan tepat waktu dengan penyimpangan kurang dari 2 detik, sementara pengiriman data ke Google Sheets mencapai tingkat keberhasilan 99,4 persen dari 500 paket yang dikirimkan.. Kelangsungan hidup bibit selama satu bulan sebesar 95,9 persen, yaitu 209 dari 218 tanaman, mengindikasikan bahwa platform terintegrasi ini mampu mempertahankan kondisi budidaya yang layak pada konfigurasi yang diuji. Hasil ini menunjukkan bahwa platform memberikan regulasi termal yang stabil, penjadwalan yang andal, dan pemantauan yang dapat diandalkan untuk budidaya skala laboratorium pada spesies ini.

1. INTRODUCTION

Bucephalandra sp. is a rheophytic aquatic plant native to Kalimantan's shaded river systems [1]. In the aquascaping trade, its unusual leaf textures and the breadth of named cultivars have pushed prices for rare forms into the hundreds of euros [2], [3]. This commercial value motivates the development of controlled cultivation methods that maintain production consistency and plant quality.

Cultivation guidance for the genus places the suitable microclimate for *Bucephalandra* sp. at air temperatures of 22 to 28 °C, relative humidity of 70 to 90 %, and low to moderate light intensity [4], [5]. Recent *in vitro* propagation work on *Bucephalandra* sp. likewise reports sensitivity to controlled environmental and light conditions during multiplication and acclimatization, consistent with a narrow tolerance window [3]. BMKG data for Lampung province report monthly mean temperatures of 26.2 to 35.2 °C [6], which frequently exceed the upper limit of this cultivation range. This thermal mismatch renders uncontrolled indoor cultivation unreliable for sustaining the quality and growth rate required for commercial production.

Ebb-and-flow subirrigation is a well-established technique in which nutrient solution periodically floods the root zone from below and subsequently drains, providing cyclic nutrient delivery and root-zone oxygenation [7]. Wang et al. [8] reported that ebb-and-flow subirrigation improved root fresh weight of tomato seedlings by 45.9 % relative to overhead sprinkling, and automated ebb-and-flow reduced water consumption in citrus liner production [9]. For emersed cultivation of

aquatic ornamentals, ebb-and-flow is particularly suited to *Bucephalandra* sp. because the cyclic alternation between moist substrate and air exposure replicates the species' natural riverine habitat [10].

Microcontroller-based IoT systems have been widely applied to plant environmental monitoring, yet significant integration gaps remain for high-value aquatic species. Zamora-Izquierdo et al. [11] developed a smart-farming IoT platform with edge and cloud computing but focused on field crops without addressing scheduled subirrigation or sensor calibration for ornamental species. Bwambale et al. [12] reviewed smart irrigation monitoring strategies and identified sensor calibration and data-transmission reliability as consistently underreported. Ayaz et al. [13] similarly noted the absence of end-to-end characterisation across the sensor, actuator, and communication layers in agricultural IoT deployments. Temperature control for plant enclosures has been studied with proportional and PID schemes [14], [15], but to the authors' knowledge this combination has not been extensively reported for aquatic ornamental cultivation on a single embedded platform.

This study addresses that gap by designing and characterising an integrated ESP32-S3 platform for laboratory-scale *Bucephalandra* sp. cultivation that combines three elements: (i) a vertical three-tier ebb-and-flow configuration with RTC-scheduled flood-drain cycling, (ii) PID fan-based ventilation control at a fixed 26 °C setpoint, and (iii) IoT environmental monitoring via Node-RED on an NVIDIA Jetson Nano edge node with HTTP telemetry to Google Sheets. For each subsystem, we asked

how well it performed against its design target: whether sensors held calibration after correction, whether the PID controller settled cleanly to the setpoint, whether the RTC kept flood-drain transitions on schedule, and whether HTTP telemetry reached the spreadsheet reliably. Flood-drain cycle parameters follow established hydroponic literature [16].

2. LITERATURE REVIEW

2.1. *Physiological Requirements of Bucephalandra sp.*

Under ex situ cultivation, temperature and humidity stability are critical environmental factors influencing photosynthesis and nutrient uptake. Direct studies on the thermal physiology of *Bucephalandra* sp. remain scarce; evidence from the closely related aquatic Araceae genus *Anubias* shows that low-temperature stress disrupts photosynthetic and metabolic function, underscoring the need to hold temperature within the cultivation range [17]. In horticultural practice, that range is given as 22 to 28 °C with 70 to 90 % relative humidity [4], [5], and recent micropropagation work on *Bucephalandra* sp. corroborates its sensitivity to controlled conditions during acclimatization [3]. The emersed method, in which plants are grown on moist substrate without full submersion, is commonly used for nursery-scale production because it facilitates light access and air circulation while preserving the alternation between wet and aerated root zones that characterises the natural riverine habitat of the genus [10]. Leaf morphology and photosynthetic capacity in such species are known to differ between submersed and emersed forms, reflecting developmental plasticity in response to aerial exposure [18].

2.2. *Ebb-and-Flow Subirrigation*

Ebb-and-flow subirrigation operates by periodically filling a planting tray with nutrient solution (flood phase) and subsequently draining it back to a reservoir (drain phase). The cyclic exchange between solution and air allows nutrient uptake during the flood phase and root-zone oxygenation during the drain phase [8]. Flood phase durations reported in the hydroponic literature typically range from 5 to

30 minutes, and drain phase durations from 20 minutes to several hours, with parameter selection depending on growing medium, plant species, and ambient conditions. Shorter flood phases with rockwool-type media are common because the medium retains sufficient moisture between cycles to prevent desiccation [16]. For emersed cultivation of *Bucephalandra* sp. on rockwool substrate, these characteristics make ebb-and-flow a suitable irrigation method, as the alternation between flood and drain phases approximates the wet-dry cycling of the species' natural riverine habitat [8], [10].

2.3. *Sensing, Control, and IoT Platform Components*

Temperature and humidity sensors. The DHT22 is a digital temperature and humidity sensor with a resolution of 0.1 °C and 0.1 % RH, an operating range of -40 to 80 °C, and manufacturer-specified accuracies of ± 0.5 °C and ± 2 to 5 % RH. The DS18B20 is a 1-wire digital temperature sensor with a programmable resolution of 9 to 12 bit, an operating range of -55 to 125 °C, and a manufacturer-specified accuracy of ± 0.5 °C over 10 to 85 °C. Both sensors communicate digitally, eliminating the analogue signal conditioning required by thermistor-based alternatives. Wardani et al. calibrated the same DHT22 against a reference thermohygrometer in a greenhouse setting and found least-squares regression brought the sensor within its ± 0.5 °C rated band. We adopt the same procedure here [19].

PID control and RTC scheduling. A ventilation fan as the sole thermal actuator limits control to one direction: the fan lowers enclosure temperature by exchanging heat with ambient air but cannot raise it. PID control computes its output from the present error, the accumulated integral of past error, and the rate of error change, balancing response speed against stability [14]. When the computed output exceeds the driver's pulse-width-modulation range, it is clamped to the nearest limit. For fixed-interval tasks such as flood-drain scheduling and daily lighting, a DS3231 RTC module keeps time through a temperature-compensated crystal oscillator. An onboard backup battery ensures programmed schedules survive power interruptions.

IoT platform and edge computing. The ESP32-S3 is a dual-core microcontroller with

integrated Wi-Fi and Bluetooth, widely used as the embedded controller in agricultural IoT systems because of its peripheral support, low power consumption, and compatibility with sensor libraries [11], [13], [20]. Node-RED is a flow-based programming environment that enables rapid construction of data pipelines and monitoring dashboards without custom server-side code [21]. Deploying Node-RED on a local edge-computing node, rather than relying solely on cloud endpoints, reduces latency and maintains monitoring continuity during intermittent internet connectivity [11]. HTTP-based telemetry to cloud spreadsheet services such as Google Sheets via Apps Script endpoints has been reported as a low-overhead data-logging strategy for resource-constrained IoT deployments.

3. METHODS

The study was conducted at the Cyber Physical System (CPS) Laboratory, Institut Teknologi Sumatera, from February to July 2025 under laboratory indoor conditions.

3.1. System Architecture

The cultivation frame is constructed from steel angle bars with overall dimensions of 120 cm × 40 cm × 150 cm (L × W × H) and contains four vertical tiers. The upper three tiers serve as

planting trays. Each tray holds *Bucephalandra* sp. seedlings in 5 cm diameter pots on rockwool medium. The lowest tier is the nutrient reservoir, with a total planting capacity of 218 pots. The walls are lined with black fibre sheeting to minimise ambient light ingress.

Twenty-four DC 12 V fans are distributed across three wall sections (12 at the rear, 6 on each side) to maintain air circulation. Above each planting tier, LED grow lights with a Red-Blue Spectrum provide supplemental lighting. A submersible pump delivers nutrient solution from the reservoir to the planting trays through distribution piping; during the drain phase, gravity returns the solution to complete the ebb-and-flow cycle. The main controller is an ESP32-S3 microcontroller connected to DHT22 sensors (air temperature and humidity), a DS18B20 sensor (water temperature), and a DS3231 RTC module via the I²C bus. Fan speed is modulated through an NPN BC547 driven by a PWM signal, and the pump and grow lights are switched through a relay module. The Node-RED monitoring interface runs on an NVIDIA Jetson Nano acting as a local edge-computing node, with real-time visualisation of sensor readings and actuator states. Figure 1 shows the block diagram of the IoT-enabled ebb-and-flow cultivation system.

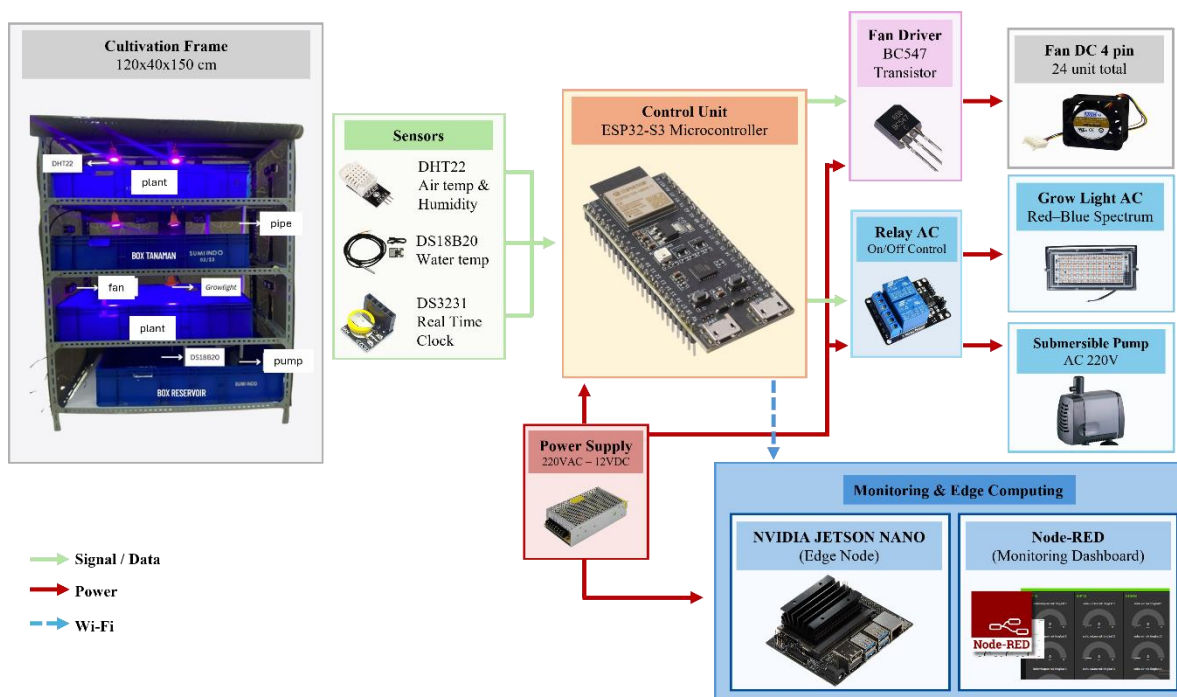


Figure 1. Block diagram of the IoT-enabled ebb-and-flow cultivation system

3.2. Ebb-and-Flow Scheduling

The DS3231 RTC drives the flood-drain cycle on a 5-minute-on, 20-minute-off schedule, producing approximately 48 flood events per 24 h. This interval falls within the range reported for ebb-and-flow systems with moisture-retaining media such as rockwool [8], [16]. When the flood phase begins, the submersible pump delivers nutrient solution to the planting trays. The pump then stops, and gravity returns the solution to the reservoir during the drain phase. Pump transition events are logged with RTC timestamps and cross-checked against an external reference clock.

3.3. PID Temperature Control Scheme

Fan ventilation is the sole thermal actuator in this enclosure. Because heat exchange occurs only between internal air and the ambient environment, the fan array can reduce enclosure temperature toward the ambient level but no further. The air-temperature setpoint is fixed at $T_{sp} = 26^\circ\text{C}$, the midpoint of the 22 to 28°C cultivation range. The fan array is driven by a PID control law whose output is mapped to an 8-bit PWM command, so that fan speed is modulated in proportion to the controller output rather than switched fully on or off. The control law is given in Equation (1).

$$u(t) = \text{sat}_0^{255} \left(K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \right) \quad (1)$$

Here $e(t) = T(t) - T_{sp}$ is the temperature error, $T(t)$ is the measured air temperature at time t , T_{sp} is the 26°C setpoint, and $u(t)$ is the PWM command to the fan driver, saturated to the range 0 to 255. The fan is activated only when the measured temperature exceeds the setpoint; below the setpoint the command is zero. Four (K_p, K_i) configurations were evaluated with K_d fixed at 1: $K_p = 500$ ($K_i = 0.02$), $K_p = 800$ ($K_i = 0.08$), $K_p = 1000$ ($K_i = 0.5$), and $K_p = 1500$ ($K_i = 0.8$).

3.4. Sensor Calibration Procedure

The DHT22 was calibrated against a UNI-T UT333 digital thermohygrometer over a temperature range of 17 to 37°C and a humidity range of 65 to 100 %, with 10 repetitions at each reference point. The DS18B20 was calibrated

against a UNI-T UT320D digital thermometer over a water-temperature range of 7.9 to 48°C , also with 10 repetitions per point. Calibration equations were derived by ordinary least-squares linear regression of sensor readings against reference values. The resulting equations were applied as firmware-level linear corrections on the ESP32-S3 before sensor values entered the control loop.

3.5. IoT Telemetry and Lighting Schedule

Sensor readings and actuator states were transmitted from the ESP32-S3 to Google Sheets via an Apps Script endpoint using HTTP POST with a JSON payload at approximately 10 s intervals. Transmission delay was defined as the difference between the RTC-synchronised device-side timestamp and the database-side receipt timestamp. Grow lights were scheduled on between 07:00 and 19:00 local time by the same RTC module that drove the flood-drain cycle. The logged sensor channels and actuator states, including the grow-light status and the RTC time, were read back from Google Sheets and visualised by the Node-RED dashboard on the Jetson Nano edge node, which polled the spreadsheet on a timestamp trigger and rendered each channel as a real-time gauge together with per-minute, per-hour, and per-week history charts. The complete user-interface flow is shown in Figure 2.

3.6. Evaluation Metrics

Sensor agreement with the reference instrument was quantified by the mean absolute error (MAE), the mean error (ME), the coefficient of variation (CV), and the mean absolute percentage error (MAPE), defined in Equations (2) to (5).

$$MAE = \frac{1}{N} \sum_{i=1}^N |x_i - x_{ref,i}| \quad (2)$$

$$ME = \frac{1}{N} \sum_{i=1}^N (x_i - x_{ref,i}) \quad (3)$$

$$CV_i = \frac{SD_i}{\bar{x}_i} \times 100\% \quad (4)$$

$$MAPE = \frac{1}{N} \sum_{i=1}^N \left| \frac{x_i - x_{ref,i}}{x_{ref,i}} \right| \times 100\% \quad (5)$$

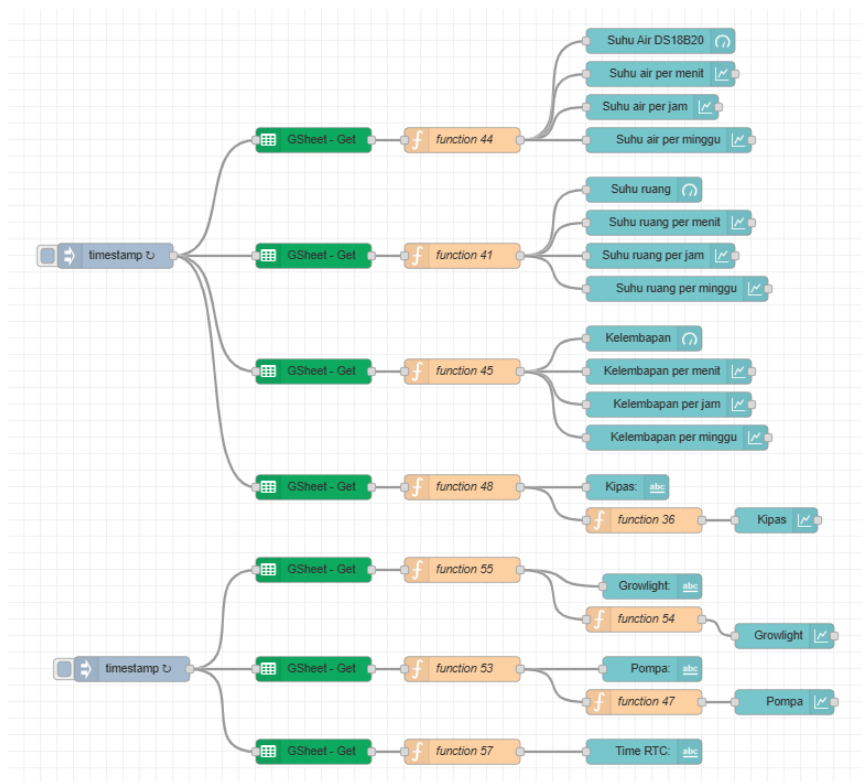


Figure 2. Node-RED user interface flow.

Here $\bar{x}_i$ is the mean of 10 repeated readings at test point i , $x_{(ref,i)}$ is the reference value, SD_i is the standard deviation across the 10 repetitions, and N is the number of test points. Temperature controller performance is characterised by three transient metrics: delay time, rise time, and settling time. Flood-drain scheduling and data-transmission performance are quantified by timing error relative to the reference clock, packet storage success rate, and mean transmission delay, respectively. Seedling survival is recorded over one month as a system-level functional observation.

4. RESULTS AND DISCUSSION

4.1. Hardware and Software Realisation

The cultivation system was assembled as specified, with 218 pots distributed across three planting tiers above a common reservoir. A dedicated panel houses the control electronics for ease of maintenance. Running on an NVIDIA Jetson Nano edge node, the Node-RED interface (Figure 3) serves three monitoring pages: air temperature and humidity, water temperature, and actuator status (pump and grow lights). Each page shows

a real-time gauge alongside history charts at per-minute, per-hour, and per-week resolutions.

4.2. Sensor Calibration

Calibration produced three linear regression equations (Table 1). All R^2 values exceeded 0.98, consistent with a strong linear fit across the tested ranges.

Table 1. Summary of sensor calibration equations

Sensor	Parameter	Equation	R^2
DHT22	Temperature	$y = 1.0092x - 0.0479$	0.9943
DHT22	Humidity	$y = 0.9928x - 3.031$	0.9890
DS18B20	Water temp.	$y = 1.0124x - 0.6461$	0.9915

The DHT22 temperature slope of 1.0092 and the DS18B20 slope of 1.0124 both deviate less than 2 % from ideal unity gain, with fixed offsets of 0.0479 °C and 0.6461 °C that the regression correction removes. For the humidity channel, the slope of 0.9928 reflects slightly lower sensitivity relative to the reference

instrument, with a 3.031 % RH offset. All three equations were applied as firmware-level linear corrections on the ESP32-S3 before sensor readings entered the control loop.

4.3. Sensor Performance After Calibration

Post-calibration evaluation was performed across operating ranges relevant to *Bucephalandra* sp. cultivation. Sensor performance is quantified by MAE, ME, MAPE, and CV as defined in Equations (2) to (5).

DHT22 temperature results appear in Table 2. At MAE 0.21 °C and MAPE 0.84 %, both within the manufacturer-specified tolerance of ± 0.5 °C, the sensor met its rated accuracy after calibration. Linear-regression calibration of low-cost temperature and humidity sensors against a reference instrument has been shown to bring such sensors within their rated tolerance [19]. The ME of +0.21 °C reflects a consistent positive bias across the entire tested range, with a maximum single-point AE of 0.46 °C at 27.0 °C. Mean CV was 0.02 %, with the non-zero value of 0.19 % at 27.0 °C the only point where the 0.1 °C sensor resolution produced any between-repetition variation. Readings in Table 2 are reported to two decimal places as produced by the calibration equation; the native sensor resolution is 0.1 °C.

Table 3 reports DHT22 humidity results. The channel produced a MAE of 3.25 % RH and a MAPE of 3.86 %, consistent with the manufacturer specification of ± 2 to 5 % RH. The ME of +3.25 % RH reflects a systematic positive bias across all tested points. A residual offset persists at mid-range values (81 to 87 % RH) after calibration. Mean CV was 0.33 %, with the highest value of 1.29 % at 90.4 % RH. As humidity is monitored for envelope detection rather than closed-loop control in this system, this level of agreement is adequate for the intended application.

DS18B20 results are reported in Table 4. At MAE 0.21 °C and MAPE 0.78 %, the sensor was more accurate than the DHT22 temperature channel. Unlike the DHT22, the ME of 0.08 °C is near zero, with signed errors alternating in direction rather than accumulating. Residual error after calibration is predominantly random. All AE values remained below 0.5 °C, with the maximum of 0.47 °C at 24.9 °C. Mean CV was

0.06 %. Because reservoir water temperature varies slowly relative to air temperature, this level of accuracy does not limit monitoring chain performance.

Table 2. DHT22 post-calibration performance : air temperature

Ref. (°C)	Sensor (°C)	AE (°C)	ME (°C)	Rel. Error (%)	CV (%)
21.2	21.24	0.04	+0.04	0.19	0.00
22.0	22.25	0.25	+0.25	1.14	0.00
23.0	23.26	0.26	+0.26	1.13	0.00
24.0	24.27	0.27	+0.27	1.13	0.00
24.9	25.28	0.38	+0.38	1.53	0.00
26.0	26.29	0.29	+0.29	1.12	0.00
27.0	27.46	0.46	+0.46	1.70	0.19
28.1	28.10	0.00	+0.00	0.00	0.00
28.8	28.81	0.01	+0.01	0.03	0.00
30.7	30.83	0.13	+0.13	0.42	0.00
Mean	—	0.21	+0.21	0.84	0.02

Table 3. DHT22 post-calibration performance : relative humidity

Ref. (%RH)	Sensor (%RH)	AE (%RH)	ME (%)	Rel. Error (%)	CV (%)
76.4	79.39	2.99	+2.99	3.91	0.10
78.5	81.92	3.42	+3.42	4.36	0.22
80.4	84.14	3.74	+3.74	4.65	0.24
81.5	86.13	4.63	+4.63	5.68	0.20
83.6	87.20	3.60	+3.60	4.31	0.12
82.5	85.90	3.40	+3.40	4.12	0.27
84.4	89.51	5.11	+5.11	6.05	0.16
88.5	92.88	4.38	+4.38	4.95	0.07
90.4	94.25	3.85	+3.85	4.26	1.29
94.5	96.27	1.77	+1.77	1.87	0.58
96.7	98.76	2.06	+2.06	3.13	0.66
100.0	100.00	0.00	+0.00	0.00	0.00
Mean	—	3.25	+3.25	3.86	0.33

Table 4. DS18B20 post-calibration performance : water temperature

Ref. (°C)	Sensor (°C)	AE (°C)	ME (°C)	Rel. Error (%)	CV (%)
21.7	21.69	0.01	-0.01	0.05	0.13
22.8	22.76	0.04	-0.04	0.18	0.11
23.4	23.39	0.01	-0.01	0.05	0.11
24.0	23.83	0.17	-0.17	0.71	0.14
24.9	24.43	0.47	-0.47	1.90	0.08
26.7	27.09	0.39	+0.39	1.46	0.00
27.4	27.02	0.38	-0.38	1.39	0.00
28.2	27.91	0.29	-0.29	1.03	0.00
29.5	29.75	0.25	+0.25	0.85	0.00
30.4	30.34	0.06	-0.06	0.21	0.06
Mean	—	0.21	-0.08	0.78	0.06

4.4. PID Controller Performance

Four (K_p , K_i) configurations were evaluated at a 26 °C setpoint with K_d fixed at 1, starting in each case from an initial air temperature slightly above the setpoint. The transient response metrics are summarised in Table 5.

Table 5. Transient response under four controller configurations

Configuration	Delay (s)	Rise (s)	Settling (s)
$K_p=500$, $K_i=0.02$, $K_d=1$	50	470	500
$K_p=800$, $K_i=0.08$, $K_d=1$	20	620	640
$K_p=1000$, $K_i=0.5$, $K_d=1$	290	280	570
$K_p=1500$, $K_i=0.8$, $K_d=1$	20	380	400

In all four cases the temperature descended monotonically to the setpoint without oscillation, and the controlled variable remained within the 22 to 28 °C cultivation range throughout. The $K_p = 1000$ configuration showed the longest delay before the descent began (290 s), consistent with its substantially larger integral gain ($K_i = 0.5$, against 0.02 to 0.08 for the lower-gain settings). The integral term accumulated error during the initial interval and produced a command component

that opposed the proportional action before the setpoint was approached, a known coupling effect when K_i is not rescaled alongside K_p . The remaining configurations reached the setpoint along comparable, well-damped trajectories [14].

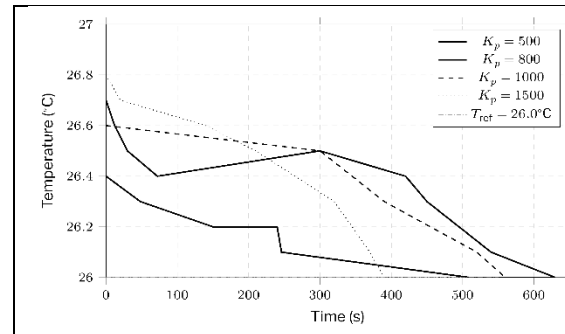


Figure 3. Transient response under the four controller configurations.

The $K_p = 500$ configuration was adopted for continued operation. It produced a smooth, fluctuation-free approach to the setpoint, and its lower gain avoids the abrupt full-speed fan cycling associated with higher gains, reducing mechanical wear over prolonged operation. The unidirectional actuator constraint did not limit performance under the tested conditions, in which ambient temperature remained above the setpoint throughout the evaluation window. Its implication at higher ambient temperatures is considered in the Conclusion. Kherkhar et al. report the same oscillation-free settling behaviour for microcontroller-based PID thermal control in a comparable closed-loop system. [15].

4.5. Ebb-and-Flow Scheduling Performance

The RTC-driven flood-drain schedule was evaluated over one continuous day. Pump switching events were cross-checked against an external reference clock. A representative segment is shown in Table 6.

All observed transitions occurred within 1 to 2 s of their scheduled time, which is negligible relative to the 5-minute flood and 20-minute drain phases. Time was retained across power cycles by the DS3231's internal backup battery, consistent with findings in comparable RTC-based IoT scheduling systems. Water-level dynamics within the trays, root-zone dissolved oxygen, and optimisation of flood and drain

durations are identified as subjects for follow-up work.

Table 6. Flood-drain pump transitions versus the reference clock

Time	Pump state	Timing error (s)
06:59:57	Off	—
07:00:01	On	+1
07:05:01	Off	+1
07:25:02	On	+2
07:30:02	Off	+2

4.6. Data-Transmission Reliability

Transmission reliability was assessed across five trials of 100 packets each. Table 7 shows that 497 of 500 packets were stored successfully, giving a storage success rate of 99.4 %. Mean transmission delay was 1 s, consistent across all ten timing measurements.

Table 7. Data transmission and storage results.

Trial	Transmitted	Stored	Lost
1	100	99	1
2	100	100	0
3	100	98	2
4	100	100	0
5	100	100	0
Total	500	497	3

The three lost packets were distributed across two trials. The most plausible cause is transient network jitter or brief congestion at the Google Sheets Apps Script endpoint. For an environmental monitoring application sampling at 10 s intervals, this loss rate is operationally acceptable. Isolated missing samples can be interpolated from adjacent readings, and a retry mechanism with local buffering would further improve reliability.

4.7. Seedling Survival Observation

During a one-month observation under the tested operating conditions (26 °C setpoint, 07:00 to 19:00 lighting, 5-minute-on/20-minute-off flood-drain cycle), 209 of 218 seedlings survived (95.9 %), and 24 of the survivors (11.5 %) produced one new leaf. No root rot or leaf damage from severe environmental stress was observed. The low

leaf emergence rate reflects the slow vegetative growth of *Bucephalandra* sp., which redirects early post-transplant energy toward root establishment rather than new foliage. This observation was made without an external control group, and survival alone does not constitute a claim of agronomic efficacy relative to alternative cultivation methods. The result does indicate that the integrated platform held conditions within the viable range for the species across the full observation period..



Figure 4. *Bucephalandra* sp. seedlings at one month; arrows indicate newly emerged leaves.

5. CONCLUSION

Sustaining a 22 to 28 °C microclimate for *Bucephalandra* sp. in Lampung's tropical climate, where ambient temperature regularly exceeds that range, was the problem this work set out to solve. The system built and characterised here met that objective on three measurable counts. Sensor measurements remained within manufacturer-specified accuracy after linear-regression calibration, the flood-drain schedule held timing to within 1 to 2 s of the reference clock, and telemetry to a cloud spreadsheet stored 99.4 % of transmitted packets. Among the four gain configurations evaluated, $K_p = 500$ gave a smooth, oscillation-free approach to the setpoint and was adopted for continued operation, with the lower gain favouring stable long-term running over aggressive correction. One-month seedling survival of 95.9 % (209 of 218) confirms that ebb-and-flow irrigation, PID fan ventilation, and edge-node monitoring operated stably and concurrently on a single embedded platform throughout the observation period. The significance of this work lies in demonstrating that these three functions, usually reported in isolation, can be consolidated on one low-cost controller for an aquatic ornamental species not previously addressed in this context.

Several limitations bound these findings. Controller characterisation was performed at a single 26 °C setpoint. More fundamentally, the enclosure cools only by exchanging heat with ambient air, so it can lower internal temperature toward, but not below, the prevailing ambient level. When ambient temperature rises above the setpoint, as commonly occurs in the Lampung climate, fan ventilation alone cannot hold the setpoint. Flood and drain durations were adopted from the hydroponic literature without optimisation for this species, and water-level dynamics and root-zone dissolved oxygen were not measured. Seedling survival was also recorded without an external control group, so no claim of agronomic efficacy is made. These boundaries define the direction of future work, most importantly active sub-ambient cooling through evaporative or ultrasonic-mist humidification capable of driving enclosure temperature below ambient, alongside multi-setpoint tuning, flood-drain optimisation with dissolved-oxygen logging, and a controlled comparison against conventional misting or drip irrigation over an extended horizon.

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