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IMPLEMENTATION OF IoT-BASED PID CONTROL SYSTEM FOR BIOACTIVE VIVARIUM

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Abstract: *This study aims to implement an Internet of Things (IoT)-based Proportional–Integral–Derivative (PID) control system for a bioactive vivarium using the ESP32 microcontroller to automate microclimate regulation. The system was developed using the Rapid Application Development (RAD) framework by integrating temperature, air humidity, and soil moisture sensors with a multi-actuator control system. PID parameters were determined through manual tuning to achieve a stable, fast response with minimal overshoot. System performance was evaluated over a ten-day testing period to assess its ability to maintain environmental conditions at predefined setpoints. The results demonstrate that the proposed system successfully maintained stable temperature, air humidity, and soil moisture within the desired thresholds. The PID feedback mechanism effectively minimized microclimate fluctuations, supported the sustainability of the vivarium ecosystem, and improved environmental control efficiency. Furthermore, integration with the Blynk platform enabled reliable real-time remote telemetry monitoring, facilitating continuous system supervision and informed decision-making by users.*

Abstrak: Penelitian ini bertujuan mengimplementasikan sistem kendali Proportional–Integral–Derivative (PID) berbasis Internet of Things (IoT) pada vivarium bioaktif menggunakan ESP32 untuk mengotomatisasi regulasi mikroklimat. Metode pengembangan menggunakan kerangka kerja Rapid Application Development (RAD) dengan mengintegrasikan sensor suhu, kelembapan udara, dan kelembapan media tanam ke dalam sistem multiaktuator. Parameter PID ditentukan melalui proses *manual tuning* untuk memperoleh respons kendali yang stabil, cepat, dan minim *overshoot*. Pengujian dilakukan selama sepuluh hari guna mengevaluasi kinerja sistem dalam mempertahankan kondisi lingkungan sesuai nilai acuan. Hasil penelitian menunjukkan bahwa sistem mampu menjaga suhu, kelembapan udara, dan kelembapan media tanam tetap stabil sesuai batas yang ditetapkan. Mekanisme umpan balik PID efektif meminimalkan fluktuasi mikroklimat, mendukung keberlangsungan ekosistem vivarium, serta meningkatkan efisiensi pengendalian lingkungan. Selain itu, integrasi platform Blynk memungkinkan pemantauan telemetri secara real-time dan jarak jauh sehingga mempermudah proses monitoring serta pengambilan keputusan oleh pengguna.

INTRODUCTION

A vivarium is an artificial enclosure or environment engineered to replicate the natural habitat of an ecosystem within a closed space (Rodman, 2021; Wüst-Ackermann et al., 2018). Vivariums are widely used to cultivate various flora and fauna by sustaining distinct environmental parameters to mirror their native origins (de Vosjoli, 1999). In its deployment, a vivarium demands precise regulation of environmental variables such as temperature, humidity, lighting, and air circulation to preserve ecosystem stability. Any misalignment in these conditions can compromise habitat equilibrium and disrupt the sustainability of the organisms living inside the vivarium (Oded & Kotler, 2010).

Bioactive is an ecosystem maintenance method that utilizes live plants, decomposing microorganisms, and substrate media to create a more natural and sustainable environment (Zhong et al., 2025). Applying this concept to a vivarium yields a bioactive vivarium system, an artificial ecosystem structured to maintain biological balance through the interplay of its internal components. Within this framework, temperature and humidity stand out as vital parameters since they directly influence microbial activity, vegetation growth, and overall ecosystem robustness. However, environmental regulation in bioactive vivariums is still predominantly executed through manual means, leaving them highly vulnerable to severe climate fluctuations caused by ambient room conditions. Therefore, an automated system is required to maintain the bioactive vivarium's microclimate continuously and reliably (Barker, 2025; Rahman et al., 2020).

The progressive expansion of Internet of Things (IoT) technology enables the execution of automated and real-time environmental monitoring and control platforms (Hercog et al., 2023). Through the cross-integration of hardware sensors, microcontrollers, and internet networks, localized climate metrics can be overseen remotely via smart devices. Beyond enhancing logging efficiency, IoT-based architectures minimize user operational workflows by eliminating the necessity for direct, on-site manual verifications (Hooshmand, 2025; Kutubuddin & Liyakat, 2024).

To preserve the stability of environmental parameters, the Proportional-Integral-Derivative (PID) control algorithm can be implemented as an automated control core (Bennett, 1993). The PID method operates by continuously calculating the immediate tracking error between the live process variable and the targeted setpoint to modulate active actuator outputs. Utilizing the PID framework is highly effective for temperature and humidity tracking because it yields swift response times, dampens sudden climate spikes, and locks the microclimate environment tightly around the targeted threshold (Borase et al., 2021; Zhang & Yang, 2024).

Several previous studies have applied IoT architectures and generic PID loops to incubator and automated greenhouse infrastructures to sustain climate baselines (Singh et al., 2023). However, the literal deployment of a PID control scheme within a bioactive vivarium setup remains largely underdeveloped, particularly concerning automated and continuous sub-surface and atmospheric microclimate integration. Furthermore, a substantial portion of prior literature centers heavily on telemetry monitoring layers without offering empirical analyses regarding closed-loop controller performance against vivarium climate volatility (Hooshmand, 2025).

Addressing these challenges, this study implements an IoT-based PID control system on a bioactive vivarium to manage temperature and humidity stability automatically. The system is built utilizing an ESP32 microcontroller, DHT22 sensors, and YL-69 probes matched with Peltier chillers, mini submersible pumps, and ultrasonic mist makers governed by a PID control loop. Beyond facilitating real-time data streaming through an IoT platform, this research evaluates the empirical capacity of the controller in defending bioactive microclimate baselines over an extended observation period.

METHOD

This study employs the Rapid Application Development (RAD) method in the process of developing a control system on an Internet of Things (IoT)-based bioactive vivarium. The RAD approach was selected as it accommodates step-by-step system development through iterative cycles of prototyping, implementation, and empirical verification. The research focuses primarily on the deployment of a localized PID control scheme to sustain temperature and humidity baselines inside the bioactive enclosure using integrated sensor-actuator layers managed by an ESP32 microcontroller.

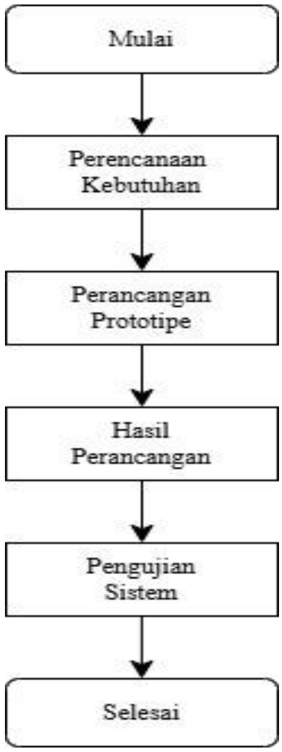

Figure 1. Research Methodology Workflow

The research workflow starts from system requirement planning, hardware and software design, localized PID algorithm implementation, up to system testing and performance evaluation. The structured methodological pipeline deployed across this study is illustrated in Figure 1.

System Design

The system is designed to perform automatic monitoring and control of environmental conditions in the bioactive vivarium. A DHT22 sensor reads the air temperature and relative humidity inside the enclosure, and the data is subsequently processed by the ESP32 microcontroller as the central processing core. The current sensor readings are constantly verified against the target setpoints to determine the appropriate mechanical response for each connected actuator.

A thermoelectric Peltier module is driven to lower the internal temperature whenever the current temperature climbs past the setpoint, whereas an ultrasonic mist maker injects moisture to boost relative humidity when atmospheric levels drop below the target. Beside running autonomous localized adjustments, the core is connected to an IoT platform to stream enclosure climate logs in real-time straight to the user's interface.

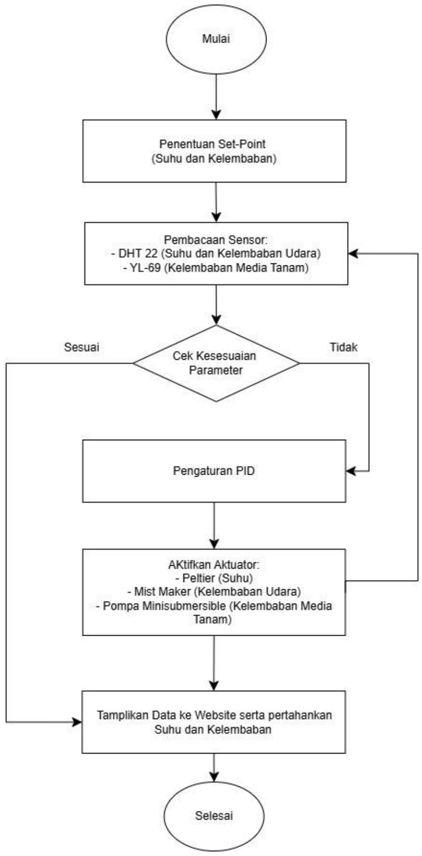

Figure 2. Unified Hardware Logic Flowchart

System Hardware

The hardware infrastructure utilized in this research consists of several primary components serving as the sensing layer, actuator layer, central processing unit, and Internet of Things communication bridge. All components are tightly linked to the ESP32 microcontroller to execute autonomous climate tracking inside the bioactive vivarium. The complete physical hardware layout utilized for this research is displayed in Figure 3.

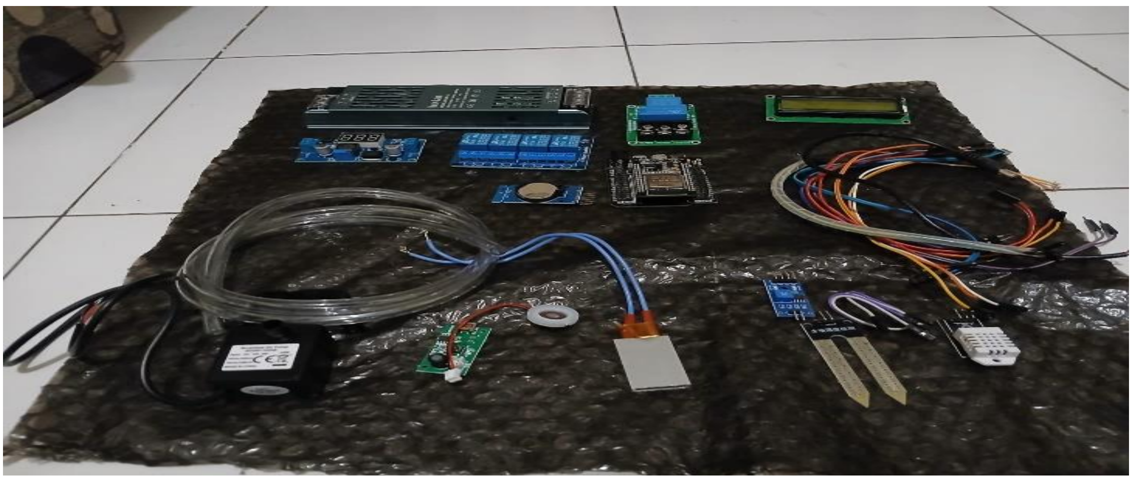

Figure 3. Main Hardware Components Layout

The system hardware layer includes the ESP32 as the central data processing unit, a DHT22 sensor to capture ambient air temperature and humidity, and a YL-69 resistive probe to assess substrate moisture content. The system employs an electromechanical relay array to switch power lines running to the high-draw actuators. The actuator layer comprises a single-stage Peltier module for active cooling, a mini submersible water pump for substrate irrigation, and an ultrasonic mist maker to handle atmospheric humidity injection. Additionally, an I2C-adapted 16x2 character LCD provides localized visual output for instant on-site data verification. To support sustainable hardware operations, an AC-to-DC switching power supply acts as the main grid feed, paired with buck step-down converters to regulate voltages safely across sensitive electronic pinouts. The entire hardware layer is bound via solid jumper leads and synced onto the cloud-connected Blynk IoT platform to enable continuous real-time telemetry streaming.

Pid Control Methodology

The classic Proportional-Integral-Derivative (PID) algorithm is implemented as the core feedback mechanism to secure microclimate baselines inside the bioactive vivarium. The algorithm functions by continuously calculating the current tracking error value based on the difference between the designated setpoint and the live sensor variable. This tracking error is then processed through proportional, integral, and derivative math blocks to yield a unified actuator command signal:

$$\mathbf{u(t)} = \boldsymbol{k_p e(t)} + \boldsymbol{k_i \int e(t)\, dt} + \boldsymbol{kd\, \frac{de(t)}{dt}} \quad (1)$$

Where:

1. $u(t)$ represents the final calculated control output signal.
2. $e(t)$ represents the current computed tracking error.
3. k_p denotes the proportional feedback gain coefficient.
4. k_i denotes the integral feedback gain coefficient.
5. kd denotes the derivative feedback gain coefficient.

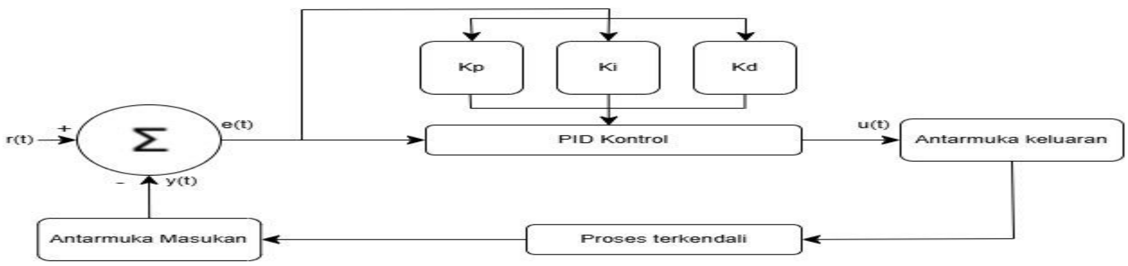

Figure 4. PID Control System

In this study, the explicit PID tracking parameters were found through an empirical manual tuning process (*trial and error*) by observing the plant's transient response curves against ambient thermal disturbances. The exact operational control coefficients applied to the microcontroller firmware are presented in Table 1.

Table 1. Manual Tuning PID Coefficients

Control Parameter Block	k_p	k_i	kd
Temperature	56.8	4.75	7.31
Humidity	90.2	0.7	1.5
Soil Moisture	9.6	4.3	6

The compiled PID gains are used to generate stable mechanical control responses, forcing air temperature, relative humidity, and soil substrate moisture to settle near the designated setpoint targets.

System Testing Framework

Empirical testing was structured to evaluate the collective performance of the sensors, actuators, and the localized PID algorithm in defending bioactive vivarium climate thresholds. The test scenarios involve verifying DHT22 data stability, testing YL-69 tracking across dry and saturated substrate beds, monitoring actuator transition steps, and validating cloud latency over the IoT connection. The unified testing matrix is outlined in Table 2.

Table 2. Comprehensive System Testing Matrix

No	Testing Category	Operational Procedure	Target Evaluation Metric
1	Sensor Calibration (DHT22 & YL-69)	Cross-verifying raw sensor logs against industrial reference glass thermometers and digital soil meters	Data tracking error margins and sensor readout stability
2	Thermoelectric Chiller Test	Forcing the Peltier cooling relay active while ambient temperature scales past setpoint	Thermal pull-down slope and actuator mechanical response
3	Ultrasonic Mist Maker Test	Activating the fogging circuit whenever relative humidity reads below target	Active humidity injection rate and moisture dispersion
4	Closed-Loop PID Evaluation	Running the enclosure continuously under strict multi-variable setpoint targets	Maximum overshoot, settling stability, and mean steady-state error
5	Cloud IoT Integration Test	Linking the ESP32 wireless transceiver directly to the remote server endpoint	Cloud transmission latency and real-time dashboard stability

RESULTS AND DISCUSSION

The hardware fabrication phase successfully merged all software routines and structural components into a unified, autonomously monitored bioactive vivarium enclosure. The controller tracks localized climate states via periodic sensor polling. Whenever internal temperature registers past the setpoint, the Peltier loop is triggered to drive down heat loads, whereas the ultrasonic mist maker activates instantly if relative humidity drops beneath the required baseline. The complete physical prototype setup during active testing is displayed in Figure 5.

Figure 5. Finished Bioactive Vivarium Enclosure Setup

Functional sensor tests indicate that the DHT22 provides stable, noise-free air temperature and humidity tracking, while the YL-69 probe accurately identifies moisture drops across dry and saturated soil beds. The initial sensor calibration benchmarks are validated in Table 3.

Table 3. Sensor Functional Validation Results

No	Sensor	Parameter	Empirical Readout
1	DHT22	Temperature	Stable, low-noise tracking
2	DHT22	Relative Humidity	Stable, consistent tracking
3	YL-69	Saturated Substrate	High analog feedback value
4	YL-69	Arid Substrate	Low analog feedback value

Following the functional verification, a continuous 10-day testing sequence was executed to monitor the system's long-term microclimate regulation capability under ambient environmental disturbances. The telemetry data logs sampled at regular 4-hour intervals are presented in Table 4.

Table 4. Microclimate Telemetry Logs Across 10-Day Continuous Run

Day	Time	Temperature (°C)	Humidity (%)	Soil Moisture (%)
1	0	24.2	80	71
1	4	24.4	79	70

1	8	24.3	79	71
1	12	24.2	80	70
1	16	24.2	79	70
1	20	24.2	81	70
2	0	24.2	80	70
2	4	24.3	79	70
2	8	24.3	79	71
2	12	24.2	80	70
2	16	23.9	79	70
2	20	24.2	81	70
3	0	24.2	80	70
3	4	24.4	79	70
3	8	24.3	79	70
3	12	24.2	80	70
3	16	24.2	79	70
3	20	24.2	81	70
4	0	24.2	80	70
4	4	24.4	79	70
4	8	24.3	79	69
4	12	24.2	80	70
4	16	24.2	79	70
4	20	24.2	81	70
5	0	24.2	80	70
5	4	24.4	79	70
5	8	24.3	79	70
5	12	24.2	80	71
5	16	24.2	79	70
5	20	24.2	81	70
6	0	24.2	80	70
6	4	24.4	79	71
6	8	24.3	79	70
6	12	24.2	80	70
6	16	24.2	79	70
6	20	24.2	81	70
7	0	24.2	80	70
7	4	24.4	79	70
7	8	24.3	79	70
7	12	24.2	80	69
7	16	24.2	79	70
7	20	24.2	81	70
8	0	24.2	80	70
8	4	24.4	79	70
8	8	24.3	79	70
8	12	24.2	80	70
8	16	24.2	79	70
8	20	24.2	81	70
9	0	24.2	80	70
9	4	24.4	79	70
9	8	24.3	79	70
9	12	24.2	80	70

9	16	24.2	79	70
9	20	24.2	81	70
10	0	24.2	80	70
10	4	24.4	79	70
10	8	24.3	79	70
10	12	24.2	80	70
10	16	24.2	79	70
10	20	24.2	81	70

The empirical tracking values recorded in Table 4 show that the manually tuned PID control loop successfully locks the vivarium microclimate parameters near the targeted thresholds over the 10-day test sequence. Internal temperature figures settle securely inside a narrow 23.9°C to 24.4°C band against the rigid 24.0°C target setpoint. Minor temperature dips noted during late-night and early-morning blocks (00:00 - 04:00) reflect lower ambient room temperatures, yet the PID controller reacts dynamically to limit steady-state errors and prevent extreme thermal drops. Relative air humidity inside the enclosure remains tightly bounded within a 79% to 81%RH span against the target baseline of 80% RH. While atmospheric humidity exhibits a natural upward trend during cooler evening cycles, the ESP32 firmware uses its asymmetric deadband logic to engage the mist maker only when parameters sink past the safe margin, protecting the plants from drying out. Substrate moisture tracking displays a much slower transient rate compared to atmospheric air parameters. Substrate moisture variables stay positioned between 69% and 71% throughout the testing run. This high degree of sub-surface stability is sustained due to the water retention capacity of the organic soil layer, which delays evaporation and interacts with the mini submersible pump's irrigation bursts to prevent root rot or saturated soil beds.

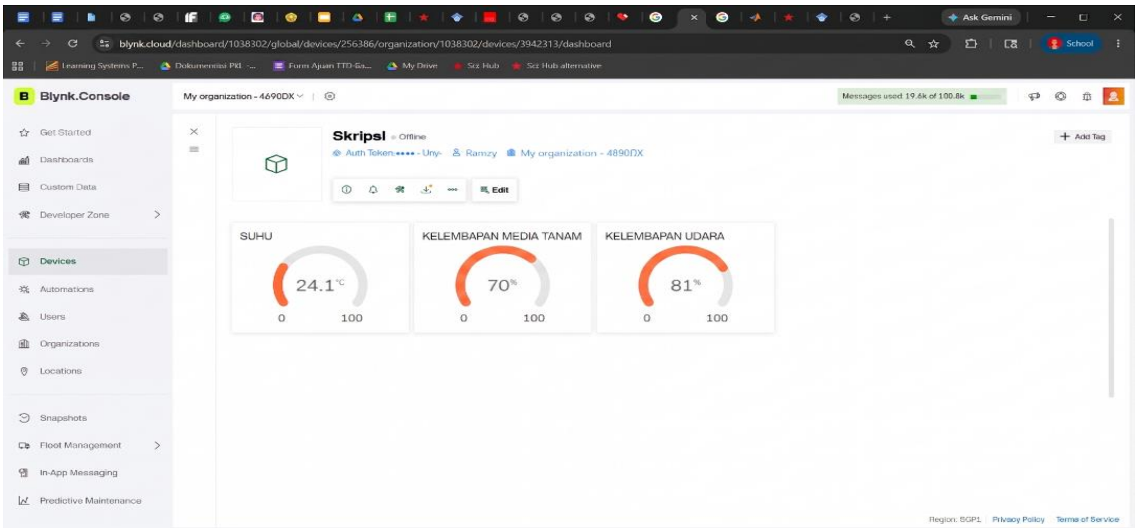

Figure 6. Blynk Dashboard

From a remote telemetry standpoint, the integration of Wi-Fi communication provides seamless access to enclosure metrics via the Blynk cloud interface shown in Figure 6. Real-time charts display the localized data streams continuously, providing users with instant remote data access and removing the need for disruptive manual checks.

CONCLUSION

Based on the successful design, hardware implementation, and empirical testing executed throughout this study, the IoT-connected PID microclimate control system demonstrates robust automated regulation of bioactive vivarium environments. The hardware prototype consisting of an ESP32 core, DHT22 sensor, YL-69 probe, Peltier chiller, ultrasonic mist maker, and irrigation loop operated reliably according to design specifications. Long-term telemetry logs across a continuous 10-day run prove that the air temperature was successfully maintained within a stable 23.9°C to 24.4°C band for a 24°C setpoint, while relative air humidity stayed locked inside a precise79% to 81% RH span against an 80% target. Concurrently, substrate moisture was held securely within a 69% to 71% margin, ensuring safe soil conditions. The manually tuned PID algorithm effectively minimizes sudden environmental overshoot without creating severe oscillations. Furthermore, real-time telemetry streaming over the Blynk platform allows for reliable, remote data monitoring. Consequently, this hardware and software integration offers an efficient, automated solution for sustaining delicate artificial tropical climates.

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