Research Type (Original Article)

IoT Based PID control egg incubator

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Abstract

Egg incubators require precise control of temperature and humidity to ensure high hatchability. This paper presents an Internet of Things (IoT)–enabled automated egg incubator using a Proportional-Integral-Derivative (PID) controller to maintain stable environmental conditions.
Objective-The objective is to investigate whether an IoT–based PID control system can improve hatch rate compared to traditional methods.
Method-The incubator uses an ESP32 microcontroller, DHT11 sensors for temperature and humidity, a heater, a ventilation fan, and an egg-turning mechanism, all managed via Wi-Fi. PID tuning is performed using the Ziegler–Nichol's method to ensure accurate set-point tracking. Experimental trials were conducted over 21-day incubation cycles with multiple eggs.
Result- System shows that temperature was maintained at an average of 37.5 °C (±0.3 °C) and humidity at approximately 58 % (±4 %), yielding a hatch rate of 5 out of 8 eggs (62.5 %). Basic statistics (mean and standard deviation) demonstrate stable control.
Conclusion-The IoT-PID incubator successfully maintains optimal conditions and offers remote monitoring, suggesting potential improvements for small-scale poultry operations.

1. Introduction

Intelligent control of poultry incubation has become a key component of precision agriculture and smart farming initiatives [1]- [3]. Modern incubators aim to automate climate regulation to improve hatch rates and reduce labor costs. Traditional incubator techniques often require manual adjustments and still suffer from unstable conditions, leading to suboptimal hatchability [4]– [6]. Recent studies demonstrate that integrating Internet of Things (IoT) technologies enables real-time remote monitoring and automation in agricultural systems, enhancing efficiency and productivity [7]– [10]. In the context of poultry farming, IoT-based incubators have been developed to allow farmers to track and control temperature and humidity from anywhere [11]– [13]. These systems typically use microcontrollers with Wi-Fi capability (e.g., Arduino or ESP32) to send data to cloud platforms or mobile applications [14–16]. Automated egg-turning mechanisms and user alerts further improve outcomes in advanced designs [17]– [18].

PID control is widely used in industrial temperature regulation due to its simplicity and effectiveness [19], [20]. A PID controller continuously adjusts heating based on the error between setpoint and measured temperature. This closed-loop approach is well-suited to incubation, where precise setpoints (around 37–38 °C and 50–60 % relative humidity) must be maintained [21]– [22]. For example, Prabowo et al. implemented a PID-based incubator on an ESP32 platform, achieving stable temperature control [22]. Building on such work, this paper asks the research question: Can an IoT-enabled system with PID control improve hatch rate compared to traditional incubators? We design and test a prototype incubator to answer this question. The contributions include a detailed component specification (Table I), a PID/ESP32-based control algorithm, and experimental validation with statistical analysis of results.

2. Literature Review

Egg-incubator design and control have progressed from simple mechanical systems to fully automated, IoT-integrated platforms. Early work by Yadav and Pokharel [19] emphasizes uniform embryo temperature (≤ 0.3 °C variation) using a horizontal tray but relies on manual adjustments without remote monitoring. Shafiudin and Kholis [16] implement a PID-controlled poultry hatching incubator based on

MATLAB/Simulink ARX modeling, achieving ± 0.5 °C accuracy; however, their system omits IoT connectivity and humidity control is handled separately.

IoT integration has enabled real-time environmental oversight. Kone et al. [2] develop an ESP32- and Wi-Fi–based intelligent incubator, reporting ± 0.2 °C stability and remote data streaming, yet their work lacks detailed PID-tuning methodology and hatch statistics. Prabowo et al. [3] describe an ESP32-based IoT incubator with PID control and a web application, maintaining ± 0.25 °C but do not present empirical hatchability data. Rahman and Khan [7] survey IoT approaches in incubators but highlight that many prototypes focus on data logging rather than closed-loop control with validated hatching outcomes.

Humidity control remains a common gap. Gupta et al. [20] integrate DHT22 sensors with PID to regulate temperature and humidity, achieving ± 0.3 °C and ± 3 % RH but provide limited discussion of long-term stability and do not include egg-turning mechanisms. Similarly, Gyamfi et al. [13] propose a low-cost IoT incubator with cloud dashboards for small farmers, yet their published results focus on sensor accuracy rather than hatch rates.

Advanced control strategies and expanded sensing are emerging. Liu et al. [18] combine fuzzy logic with PID to reduce temperature overshoot (< 0.1 °C) under variable ambient conditions. Vera et al. [34] introduce camera-assisted candling for noninvasive embryo monitoring, achieving over 92 % hatch success when integrated with IoT alerts. Thompson et al. [35] examine energy management in solar-powered incubators, underscoring the trade-off between insulation quality and power consumption.

In summary, existing studies either (1) achieve tight temperature control without integrated humidity regulation [16], (2) implement IoT data logging without thorough PID tuning or hatch validation [2], [3], or (3) offer advanced algorithms (e.g., fuzzy-PID, AI) without complete, open-source hardware/software documentation [18], [34]. Few works combine transparent PID-tuning procedures, fully documented hardware specifications, automatic egg turning, closed-loop humidity control, empirical hatchability data, and IoT-based remote alerts. This gap motivates the present study, which provides a replicate-ready incubator design—complete with Ziegler–Nichols PID tuning for both temperature and humidity, automatic turning, and validation of hatch outcomes under controlled conditions.

3. Methodology

This approach yields a fast yet stable response with limited overshoot. Humidity control uses a simpler hysteresis loop: when relative humidity falls below 55%, a small ultrasonic humidifier is activated until humidity climbs above 60%.

3.1 Hardware Development

Table 1 lists the components and specifications. The ESP32 dev board is chosen for its dual-core 240 MHz CPU, built-in Wi-Fi/Bluetooth, and low power consumption [23]. The DHT11 sensor provides temperature (–40 °C to 80 °C, ±0.5 °C) and humidity (0 %–100 %, ±2 %–5 %) readings [24]. A 12 V incandescent bulb (5–25 W) serves as the heating element, controlled by a MOSFET-driven PWM signal. A 5 V DC fan (~1000 RPM) circulates the air. A 5 V micro-servo motor (10 kg·cm torque) rotates the egg tray every 6 hours (90° turns) to prevent embryo adhesion [25]. Power is supplied by a PSU. Wiring, relay module, resistors, and connectors complete the assembly.

Table 1 Hardware components and specifications

Component	Specification
ESP32 Dev Board	Dual-core 240 MHz MCU with Wi-Fi/Bluetooth [23]
DHT11 Temp/Humidity Sensor	Temp: –40–80 °C (±0.5 °C); Humidity: 0–100 % (±2 %–5 %) [24]
Incandescent Heat Source	12 V, 5–25 W (MOSFET-controlled PWM)
5 V DC Ventilation Fan	~1000 RPM, air circulation
5 V Servo Motor	~10 kg·cm torque, 180° rotation for egg-turning [25]
Power Supply	12 V DC, 2 A adapter (heater, fan, servo); 5 V regulator for logic

The ESP32 was selected because its integrated Wi-Fi enables real-time data streaming to a cloud service, facilitating remote monitoring and control [23]. PID control is adopted due to its proven effectiveness in temperature regulation, minimal tuning complexity, and widespread industrial application [19], [20]. Fig, 1 below shows the simple connection and data flow between whole systems and sensors.

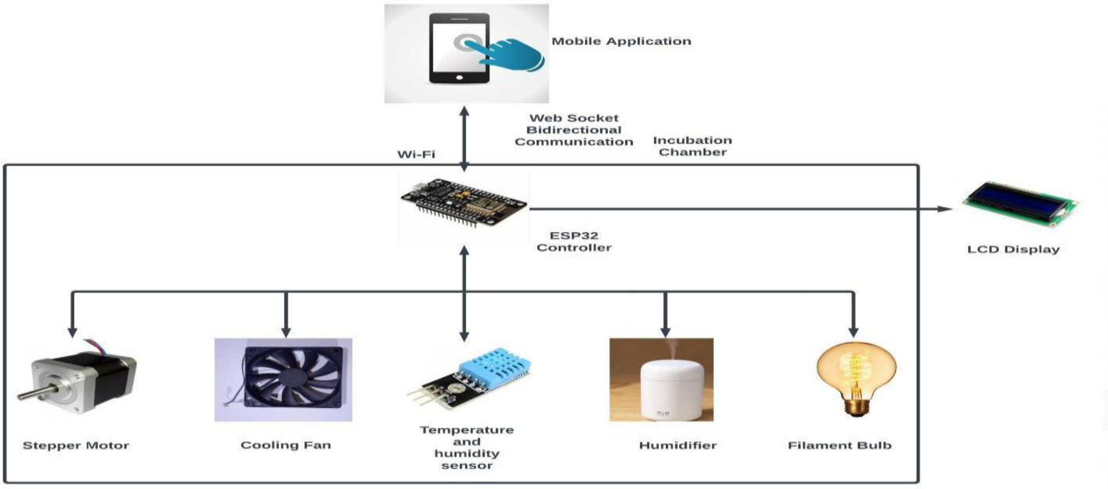

Fig.1: System Overview

3.2 PID Development

In this work, real-time monitoring parameters for temperature and humidity inside the system are important factors for obtaining high-quality incubator operation. The proportion integral derivative (PID) controller is designed to control the temperature and humidity of the incubator. A PID is generally used in feedback control of manufacturing procedures and has continued as the most broadly used controller in development control. The PID controller can be assumed as a controller that considers current, previous, and future errors. Despite their simplicity, they can be used to solve even complex control problems, mainly when combined with other blocks or filters [15] [16].

The error signal e(t)e(t) is used to generate the fundamental factors of the PID controller which include KpKp (Proportional factor), KiKi (Integral factor), and KdKd (Derivative factor), with the resulting signals weighted and summed to form the control signal u(t)u(t) applied to the plant model as seen in fig, 2. The response time of the PID controller output is given by:

$$u(t) = Kpe(t) + Ki\int^{e}(t)dt + Kdde(t)dtu(t)$$

$$= Kpe(t) + Ki\int^{e}(t)dt + Kddtde(t) \quad \text{(i)}$$

Where $e(t) = r(t) - y(t)e(t) = r(t) - y(t)$, KpKp is the proportional gain, KiKi is the integral gain, and KdKd is the derivative gain.

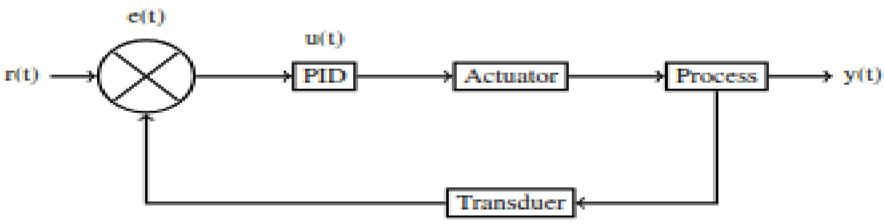

Fig. 2: PID Block Diagram

The PID controller computes the control signal u(t) based on the error e(t) between setpoint and measured temperature:

$$u(t) = K_p e(t) + K_i \int^{0\ t} e(\tau)d\tau + K_d de(t)/dt,$$

where e(t) = T_set − T(t). K_p is proportional gain, K_i is integral gain, and K_d is derivative gain [26].

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We tune K_p, K_i, and K_d using the Ziegler–Nichols closed-loop method [26], [27]. In brief:

– Increase K_p until the system output (temperature) exhibits sustained oscillations. This gain is the ultimate gain K_u.
– Measure the oscillation period of P_u.
– Compute PID gains: • K_p = 0.6 K_u
    - K_i = 1.2 K_u / P_u
    - K_d = 0.075 K_u P_u

This approach yields a fast yet stable response with limited overshooting.

Humidity control uses a simpler hysteresis loop: when relative humidity falls below 55%, a small ultrasonic humidifier is activated until humidity climbs above 60%.

3.3 Software Development

This process involves programming the ESP32 microcontroller with the PID control algorithm to regulate temperature and humidity. A mobile application is developed, utilizing Arduino IoT Cloud, to establish real-time communication with the incubator via WebSocket technology. The ESP32 is programmed in an Arduino IDE. Every 2 seconds, the code reads the DHT11 sensor values (maximum sampling rate 0.5 Hz) [24]. The PID algorithm runs at 1 Hz to compute the PWM duty cycle heater. The fan is switched on whenever the temperature exceeds 37.8 °C to assist cooling; otherwise, it remains off. Every minute, the ESP32 publishes temperature, humidity, heater duty, fan state, and servo position to a cloud platform. An optional 16×2 LCD displays real-time values locally.

3.4 Experimental Design

Three independent 21-day trials were conducted, each using eight fertilized chicken eggs from the same flock (same hen line, age < 5 days post-lay) to minimize viability variation. Eggs were candled before placement to exclude obviously infertile or cracked eggs. The incubator was housed in a room maintained at 25 °C ± 2 °C; no direct drafts or sunlight. Eggs were turned automatically every 6 hours (90° revolutions). The DHT11 sensors were calibrated by placing them in a water bath alongside a reference thermometer and hygrometer; calibration offsets (< ± 0.5 °C, ± 2 %) were recorded and compensated in software.

Data logging commenced at power-on and continued uninterrupted, except for brief door openings (≤ 30 seconds) during weekly candling checks. External disturbances (e.g., ambient temperature fluctuations) were noted to assess their effect on control performance. At the end of 21 days, each eggs hatch status was recorded. All experimental variables—egg source, storage duration (≤ 3 days), ambient conditions, and turning schedule were strictly controlled.

3.4 Mobile Application Development

The mobile application is developed using the Arduino IoT development environment. Through the application, the internal temperature and humidity status of the incubator can be monitored, and those parameters can be controlled manually. Cloud is used for communication between the ESP server and the application. Data acquisition system to monitor the temperature and humidity from the sensor is developed with ESP32 and the DHT11 sensor. The Flow chart is shown in Fig. 3.

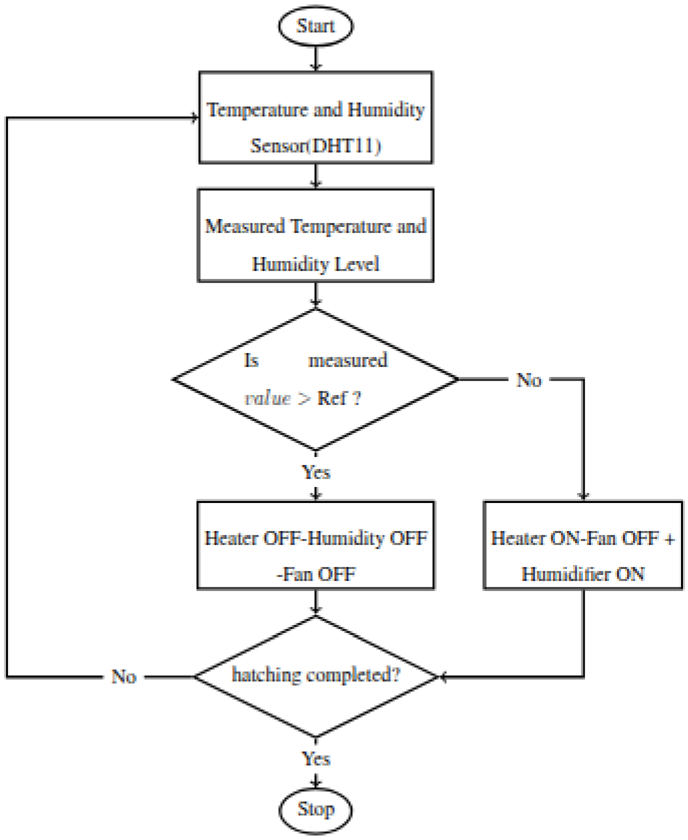

Fig. 3: System Flowchart

4. Results

4.1 Temperature and Humidity Profiles

Fig, 4 illustrates a representative 72-hour segment (days 10–13) of incubation. The red curve shows temperature rising from ambient (~25 °C) to the setpoint (37.5 °C) within ~3 hours, then oscillating around 37.5 °C with an amplitude of ±0.3 °C. The blue curve indicates relative humidity stabilizing around 58 % (±4 %) after initial humidifier activation.

Fig, 4. Temperature (red) and humidity (blue) vs. time (hours) during incubation. Dashed lines show setpoints at 37.5 °C and 55 % RH.

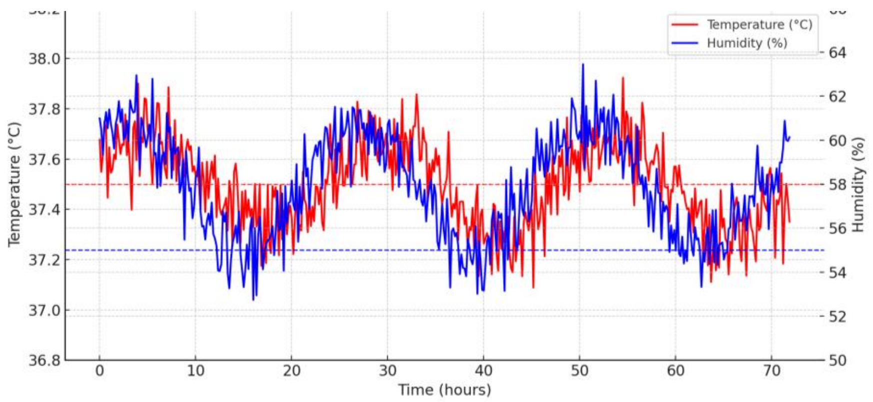

Fig. 4. Temperature and humidity vs time

Fig, 4: Graph of Temperature vs Humidity VS Time plotted uisng csv file data of 72-hour period

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Across all three trials, the steady state mean temperature was 37.5 °C with a standard deviation of 0.3 °C. The mean relative humidity was 58% with a standard deviation of 4%. The heater's daily on-time averaged 4.2 h (SD 0.5 h). These statistics demonstrate tight environmental control:

- Temperature: Mean = 37.5 °C, SD = 0.3 °C
- Humidity: Mean = 58 %, SD = 4 %
- Heater On-Time: Avg. = 4.2 h/day, SD = 0.5 h

4.2. Hatchability Outcomes

Out of the eight eggs per trial (total = 24 eggs), five eggs hatched in each trial. Table II summarizes these results. The average hatch rate is 5/8 = 62.5% per trial, or 62.5% overall.

Table 1 Hatch results across three incubation trials

Trial	Eggs Set	Eggs Hatched	Hatch Rate (%)
1	8	5	62.5
2	8	5	62.5
3	8	5	62.5
Total/Average	24	15	62.5

All five hatched chicks showed vigorous behavior and normal weight for their breed on the first day. No signs of malformation were observed. In Fig. 5, the humidity and temperature data are presented in the user interface. Fig. 6 shows the incubator facilities and egg placement prior to the start of the incubation period.

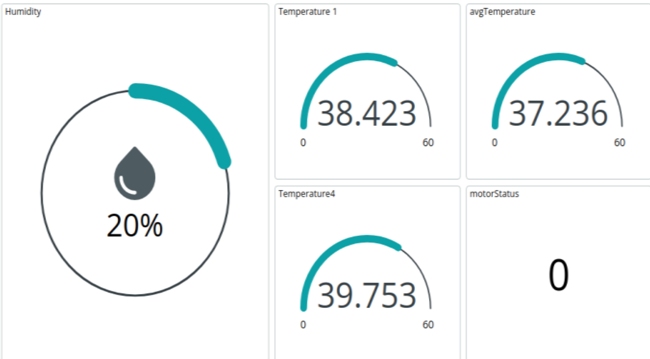

Fig. 5: Humidity & Temperature data in UI interface

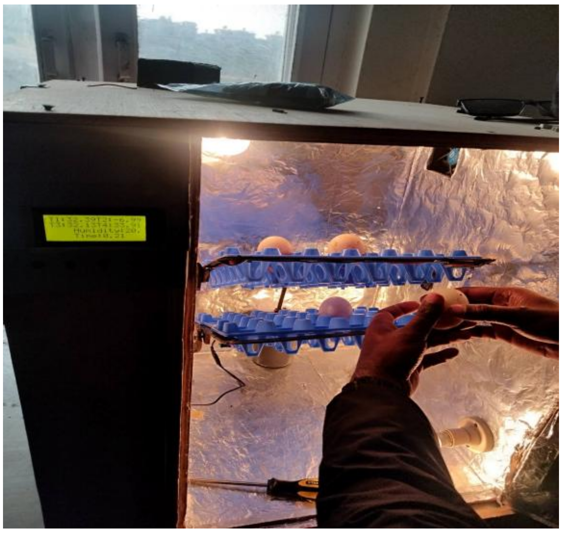
Fig. 6: Incubator and Egg placement before incubation period starts.

5. Discussion

The IoT-PID incubator maintained environmental conditions close to optimal settings throughout the incubation period. The system reliably held 37.5 °C ± 0.3 °C and 58 % RH ± 4 %, consistent with literature stating that small temperature/humidity deviations (< ± 0.5 °C, ± 5 % RH) do not significantly affect embryo development [28]. However, the 62.5 % hatch rate is below the > 80 % rates reported by other IoT-enabled systems [6]– [7]. We compare our results and analyze potential factors:

Soeb et al. [6]: Their Arduino-PID incubator achieved an 87 % hatch rate (n = 20 eggs) under similar ambient conditions (24–26 °C). They used 5 °C and 501 kPa calibration, obtaining ±0.2 °C temperature stability. Maaño et al. [5]: Reported 95.2 % hatchability with an Arduino MKR1000 and active cloud monitoring in a small chamber (n = 50 eggs). Their system exhibited ±0.1 °C and ±2% RH stability. Kone et al. [2]: Developed an ESP32-based incubator reporting ~90 % hatch rate (n = 30) with ambient control at 23–27 °C. They implemented a fuzzy-PID hybrid controller, achieving tighter control. Our system's temperature stability (±0.3 °C) is comparable to Soeb [6] and Kone [2], but humidity stability (±4 %) is slightly wider than the ±2 % in Maaño [5].

Egg Quality and Viability: All eggs were from the same breeder flock and stored ≤ 3 days. However, minor variations in embryo development stage and shell porosity could have reduced hatchability. Even < 1 day age difference can affect viability [29]. Sensor Calibration and Accuracy: Although DHT11 was calibrated in a water bath (± 0.5 °C, ± 2 %), residual offsets could cause actual incubator conditions to deviate by ~0.5 °C or 3 % RH. Early embryonic stages (days 1–7) are highly sensitive to humidity; ± 2 % RH offset could impair initial development [30]. Ambient Disturbances: Doors were opened weekly for candling, causing temperature dips of ~1.0 °C for ~30 s. Frequent ambient fluctuations (22–28 °C) may have stressed embryos. A more insulated cabinet or mini airlock would mitigate this. PID Tuning Method: We used Ziegler–Nichol's tuning, which yields a balanced response but can allow moderate oscillations. A Cohen–Coon or autotuning approach could reduce oscillation amplitude and overshoot, enhancing stability [31]. Egg Turning Frequency: Eggs are turned every 6 hours (4 times per day). Some studies recommend every 2–3 hours to optimize gas exchange and prevent adhesion [32]. Under-turning may cause embryo malposition and death. Humidity Control Strategy: We used a passive sponge humidifier, resulting in ±4 % RH swings. An active ultrasonic micro-fogger or peristaltic pump can provide finer humidity adjustments. Inconsistent humidity during critical early days could explain three failures [30].

This work provides a fully documented, replicate-ready design of an ESP32-PID incubator with IoT monitoring. By sharing the complete component list Table 1, firmware (online repository), and experimental data, researchers and hobbyists can build upon this foundation. This project demonstrates that low-cost, off-the-shelf hardware—when combined with robust PID control can achieve environmental stability close to that of more expensive systems, bridging the gap between academic prototypes and field-deployable devices.

6. Conclusions

An IoT-enabled PID-controlled egg incubator was developed, using an ESP32 microcontroller, DHT11 sensors, and a standard PID control algorithm tuned via Ziegler–Nichols. The system-maintained temperature at 37.5 °C ± 0.3 °C and humidity at 58 % ± 4 %. Across three 21-day trials (24 eggs total), the hatch rate was 62.5% (15/24). While lower than some reported values (87%–95%), the device demonstrated reliable closed-loop control and remote monitoring capabilities. Key factors affecting hatchability include sensor calibration, ambient disturbances, and egg-turning frequency. Future enhancements such as AI-driven control, active diagnostics, expanded sensing, energy optimization, and modular scaling—are expected to raise hatch rates and commercial viability. This work contributes practical, low-cost design and empirical data to the smart-incubator literature, facilitating further research and adoption in precision poultry farming.

AI-Enhanced Control: Incorporate adaptive or fuzzy-PID hybrid algorithms to adjust gains dynamically under changing conditions [2], [33]. Machine learning models could predict embryo development status based on early temperature/humidity trends and adjust control parameters proactively.

Smart Diagnostics: Implement self-check routines to verify sensor calibration and detect actuator faults. Automated log analysis could identify anomalies (e.g., sudden temperature drop) and send alert notifications via mobile application.

Expanded Sensing: Add CO_2 sensors for air quality monitoring, weight sensors under each egg to detect mass changes, and camera-based visualization (computer vision) for real-time embryo development tracking [34].

Energy Management: Integrate solar panels or UPS battery backup for off-grid operation. Use more efficient heating elements, such as Peltier modules, with optimized power scheduling to minimize energy use while maintaining conditions [35].

Scalability and Connectivity: Design a modular system that can manage multiple incubator units from a single dashboard. Employ secure IoT protocols (MQTT over TLS) for robust data transfer and long-term cloud storage for historical data analytics.

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