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Design and development of a solar energy-based egg incubator using the quality function deployment method with an automatic sliding rack

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Abstract

This research focuses on the design and development of a solar-powered egg incubator specifically for free-range chickens, incorporating an automated sliding rack mechanism. One of the main issues encountered by poultry farmers is the inconsistency of electricity supply and the uneven distribution of heat within conventional incubators, both of which contribute to low hatch rates. To address this, the study employed the Quality Function Deployment (QFD) methodology alongside the House of Quality (HOQ) framework to systematically convert user requirements into engineering specifications. Primary data were gathered through Focus Group Discussions (FGD) with poultry practitioners, followed by experimental evaluations concerning thermal distribution performance and the reliability of the solar-powered backup system. Findings demonstrate that the integration of the automated rack and solar panel system resulted in a full (100%) hatching rate, with a stable incubation temperature maintained within the optimal range of 37 to 40°C. Additionally, the solar energy system ensured uninterrupted operation for approximately 7 hours in the event of a power outage. This technological innovation offers a sustainable, eco-friendly solution that holds the potential to significantly boost the productivity of local poultry farming.

Keywords:
Egg incubator, solar panel, automatic sliding rack, QFD, and renewable energy.

1 Introduction

Free-range chickens constitute a vital source of animal protein for the Indonesian population, particularly in rural and peri-urban areas. In West Java, the production of free-range chickens saw a marked rise, reaching 30,213 tons by 2023. Nevertheless, this growth trend reversed in 2024, showing a recorded decline of 4.82% based on figures released by Open Data Jabar [1]. One of the technological breakthroughs developed to support poultry production is the artificial incubator, which enables a greater volume and better synchronization of egg hatching compared to traditional natural methods. However, these incubators still face two persistent challenges: the unreliability of electricity provided by the national grid (PLN) and inconsistent heat distribution within the incubation chamber. These issues often lead to less-than-ideal incubation conditions, ultimately resulting in reduced hatching success rates and compromised chick quality. To address these shortcomings, there is a pressing need to develop a hybrid incubation system that incorporates solar energy as a renewable backup source, combined with an automated mechanism for egg turning. This innovation is expected to enhance temperature uniformity and create optimal conditions for embryo development, thereby boosting hatchability and improving productivity in free-range poultry operations.

The use of controlled incubators as a method of artificial incubation serves as an effective alternative to natural brooding, successfully mimicking the environmental conditions typically provided by a hen during embryo growth. This approach allows for simultaneous hatching on a larger scale, significantly improving the efficiency of poultry breeding systems. Prior research [2][3] suggests that the ideal environmental settings for incubating free-range chicken (*ayam buras*) eggs include maintaining a temperature range of 37 to 40°C and relative humidity levels between 50% and 60%. Consistently preserving these conditions is essential to ensure successful embryogenesis and high hatching rates.

Therefore, the primary objective of this study is to design and develop a hybrid incubation system that addresses these issues. This is achieved by incorporating solar energy as a renewable backup power source and integrating an automated sliding rack mechanism to ensure uniform heat distribution. This innovation is expected to create optimal conditions for embryo development, thereby boosting hatchability and improving productivity in free-range poultry operations [4].

1.1 Dry cell battery

The use of dry batteries (Fig. 1) is suitable for egg incubators for local chicken eggs, as they eliminate the need for periodic maintenance and offer greater durability and longevity compared to wet batteries. With a specification of 12V–12Ah and 3–7A, this battery can operate continuously for up to 7 hours [5].

The choice of a Sealed Lead-Acid (SLA) dry battery is based on its maintenance-free nature and reliability for off-grid power systems, making it a practical choice for rural agricultural applications [6].

Fig. 1. Dry cell battery.

1.2 Solar panel

Photovoltaic (PV) cell assemblies are engineered to convert solar irradiance into electrical energy through the photovoltaic effect. In this application, a solar panel rated at 60 watts and 12 volts is utilized to power a 19-watt incubator while simultaneously providing charging capabilities for a 12V, 12Ah rechargeable battery. The solar panel (Fig. 2) is designed with a compact form factor measuring 50×40×0.3 cm, making it suitable for space-constrained installations. Furthermore, it is constructed with an ingress protection rating of IP65, ensuring reliable performance in outdoor environments by offering resistance against dust and low-pressure water exposure [7].

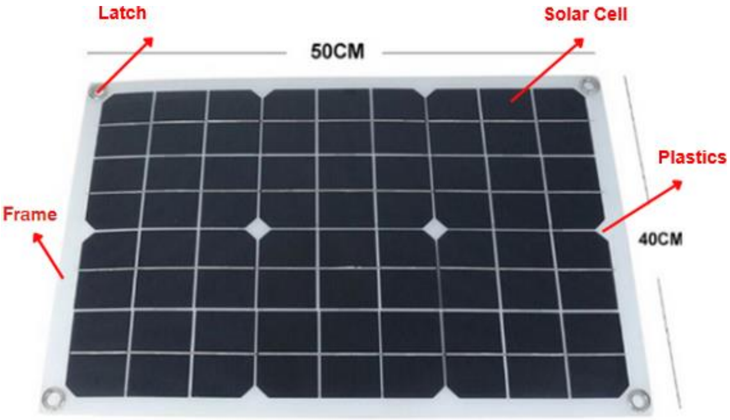

Fig. 2. Solar panel.

1.3 Auto switcher for dual power backup

The device (Fig. 3) serves a critical role as an automated transfer mechanism between the main utility grid (PLN) and the backup battery system in the event of electrical disruptions. Its implementation is essential to maintain an uninterrupted power supply, thereby ensuring the reliability and continuity of operational processes [8].

Fig. 3. Auto switch DC - DC 220V dual power backup.

1.4 Incandescent lamps

Incandescent lamps (Fig. 4) constitute a type of artificial lighting device that generates visible light through the resistive heating of a metallic filament, typically tungsten, when an electric current is applied. This filament reaches high temperatures sufficient to emit light and is encapsulated within a sealed glass enclosure. The primary role of this enclosure is to isolate the filament from atmospheric oxygen, thereby mitigating oxidative degradation and extending the operational lifespan of the lamp [9].

Beyond their principal function as light emitters, incandescent lamps are also employed in applications where thermal energy is desirable. A notable example includes their integration into thermal systems such as incubators used for hatching local poultry eggs, wherein the heat produced contributes to maintaining optimal incubation temperatures [9]. Incandescent lamps were selected not only for their lighting function but, more importantly, as a stable heat source. They deliver consistent and easily regulated thermal energy, making them a widely used and cost-effective solution for maintaining optimal temperatures in small-scale incubators [10].

Fig. 4. Incandescent lamp.

1.5 Digital thermostat

A digital thermostat (Fig. 5) is a device that functions to detect temperature within a system, thereby enabling the temperature to be maintained near a predetermined set point value. Its primary function is to measure and regulate temperature stability. When the temperature reaches the preset value, the relay will either switch on or off, depending on the selected mode whether it is used for heating or cooling purposes [11].

Fig. 5. Digital thermostat.

1.6 Rotating dynamo

The rotating dynamo, which is coupled with a hook and structural support (Fig. 6), functions as the main actuator responsible for rotating the egg rack to maintain uniform and optimal surface temperatures across all eggs. Its operation is controlled automatically through a digital timer that regulates activation cycles at predetermined intervals. This timing mechanism is essential for maintaining thermal stability throughout the incubation period, thereby improving the overall system's performance and operational reliability [12].

Fig. 6. Rotating dynamo.

1.7 Digital timer

In this study, the DH48S-S digital timer (Fig. 7) was utilized to accurately regulate the activation intervals of the dynamo, which plays a vital role in preserving thermal consistency during the incubation process. The timer's high level of precision allows for stable and consistent cycling, thereby promoting uniform heat distribution across the entire surface of the eggs. Achieving such temperature uniformity is crucial for proper embryonic development, as any fluctuations or localized overheating can adversely affect hatching success. Implementing this type of digital control system significantly improves both the reliability and operational efficiency of the incubation apparatus [11].

Fig. 7. DH 48S-S digital timer.

1.8 Direct current fan

A Direct Current (DC) fan (Fig. 8) serves a vital function in preserving stable environmental conditions within an incubator by enabling continuous and even airflow throughout the chamber. This airflow mechanism plays an important role in maintaining uniform temperature and humidity distribution, which in turn supports the overall consistency and dependability of the incubation process. Such uniformity is particularly crucial in applications that demand high precision in environmental regulation, including biological incubation and material testing processes [11].

Fig. 8. DC fan.

1.9 Radiation heat transfer

This study employs a mixed-methods approach, integrating qualitative and quantitative techniques to thoroughly explore and address the research objectives. On the qualitative side, methods such as Focus Group Discussions (FGDs) and the Quality Function Deployment (QFD) framework are utilized to systematically gather insights from experts and end users. In parallel, the quantitative component involves empirical testing, including accurate temperature monitoring and controlled egg incubation trials, to substantiate the findings with measurable data (Eq. (1)). By combining these two approaches, the research seeks to strengthen both the credibility and depth of its conclusions through a process of methodological triangulation [13].

$$P = e\,\sigma\,A\,T^4 \tag{1}$$

P = radiation power (W = J/s)
A = surface area (m^2)
σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4)
e = emissivity
T = temperature (K)

1.10 QFD

QFD represents a structured approach widely utilized in product design and development, with a core objective of systematically identifying and integrating customer needs into the engineering process [14]. This method typically relies on qualitative techniques such as focus group discussions to uncover and articulate specific user demands—in this context, those of livestock farmers—which then serve as the foundational input for determining user-driven design priorities within the QFD framework [15]. A key instrument within this methodology is the House of Quality (Fig. 9), a comprehensive matrix that establishes a relationship between customer requirements (the "what") and corresponding technical or functional responses (the "how"). The matrix incorporates multiple analytical elements, including weighting of priorities, interrelationships among technical responses, and suggested directions for enhancement, thereby enabling a coherent transformation of user expectations into precise and actionable engineering specifications [16].

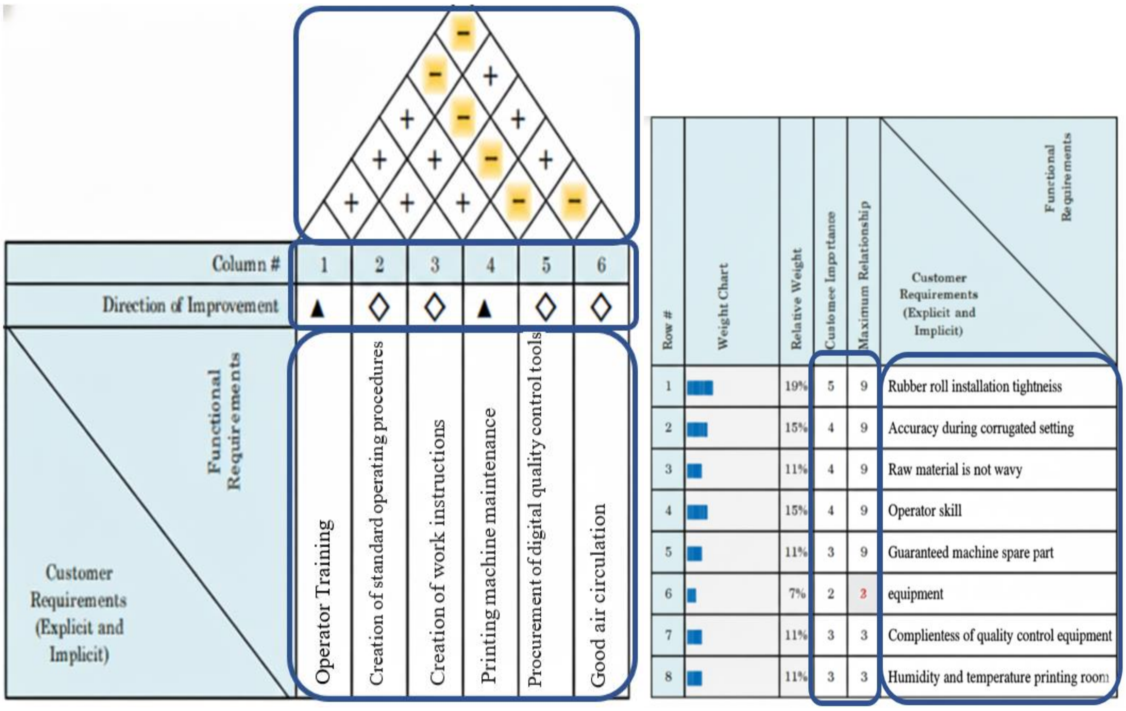

Fig. 9. House of quality.

2 Research method

2.1 Type of research

This study employs a mixed-methods approach, integrating both qualitative and quantitative strategies to effectively address its research goals. On the qualitative side, methods such as FGDs and the implementation of QFD are utilized to systematically gather insights from experts and end users. Complementing this, the quantitative component comprises empirical activities, including accurate temperature monitoring and structured hatching trials, to support the conclusions with measurable evidence. The combination of these methodologies is intended to strengthen both the reliability and validity of the research findings through a process of methodological triangulation.

2.2 Tools and materials

The supporting tools encompass various components that enable the efficient operation of the incubator, such as solar panels and batteries as renewable power sources, a microcontroller (Arduino) for temperature and humidity regulation, and auxiliary devices including fans, lamps, and pumps to maintain an optimal incubation environment. Meanwhile, consumable materials such as insulation, soldering tin, and electrical wires are used to assemble the electronic circuits connecting all components. Structural materials such as wooden frames and multiplex boards are employed to construct the body and enclosure of the incubator. The synergy of these materials contributes to the creation of a stable and effective system for the egg incubation process.

2.3 Experimental setup

The experimental setup for this project comprised a series of systematically organized procedures. First, the incubator frame was assembled, followed by the installation of a solar panel positioned in a location with direct sunlight exposure. The panel was connected to a battery and a power controller to establish the renewable energy supply. Subsequently, the internal system was configured by connecting the Arduino microcontroller with sensors, a pump, a lamp, a fan, and a timer. The system was programmed to maintain an internal temperature range of 37–40°C and a relative humidity of 50–60%. Eggs were then placed on a sliding rack, which was connected to a motor (dynamo) programmed to rotate at predetermined intervals. Continuous monitoring of temperature and humidity was conducted through an LCD interface, and the power consumption of the incubator was recorded for performance analysis. A power backup test was performed by simulating a power outage, observing the system’s automatic switchover response and operational duration. The final stage involved evaluating the incubation performance over a period of 21 to 28 days, during which the hatching success rate was calculated, and the stability of the temperature and humidity levels was documented.

2.4 Heat transfer measurement point

In this research, temperature measurements were systematically performed at three specific points on the automatic sliding rack using a non-contact infrared thermometer (thermo gun). These measurements were taken twice each day, once during the daytime and once at night, to capture temperature fluctuations under varying ambient conditions. The resulting temperature data were then used as the foundation for calculating radiative heat transfer, a crucial indicator for evaluating the thermal performance and energy efficiency of the automated sliding system (Fig. 10).

This approach provides a more in-depth understanding of the system’s operational characteristics when exposed to changing environmental conditions, thereby supporting improvements in the design and control strategies for automation systems that are sensitive to thermal dynamics. The objective of this procedure was not to perform complex heat transfer calculations, but rather to empirically verify the system's ability to maintain a uniform temperature distribution across the entire rack. Ensuring that all eggs are exposed to a consistent temperature within the optimal range (37-40°C) is a critical factor for achieving a high and uniform hatching rate, which was a primary technical goal of this study.

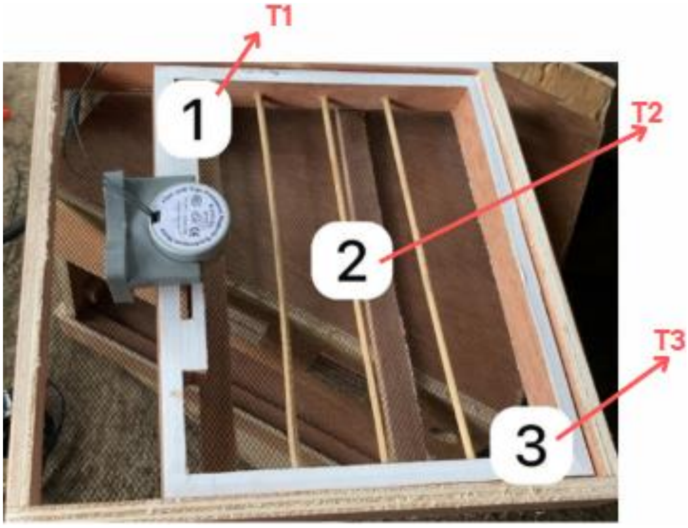

Fig. 10. Heat transfer measurement point.

2.5 Data collection method

The data collection process employed the FGD method involving selected livestock farmers as participants. This qualitative approach was intended to elicit detailed insights necessary for constructing the consumer requirements matrix, as well as identifying the functional attributes of the equipment, which were subsequently integrated into the House of Quality (HOQ) framework.

3 Results and discussion

3.1 FGD

As an initial step, a FGD was conducted with three poultry farmers to explore their experiences and needs related to free-range chicken egg incubators. The data were obtained: (1) farmer 1 uses a simple homemade incubator (fan, incandescent lamp, water container) with a manual thermostat that frequently malfunctions; (2) farmer 2 monitors temperature and humidity using a hygrometer, although the readings are occasionally inaccurate; (3) farmer 3 still relies on natural incubation by brooding hens.

The results of the FGD illustrate that the diversity of incubation methods reflects a strong demand for a more reliable incubator that is user-friendly and does not require frequent manual intervention.

3.2 Identifying consumer needs and defining technical specifications

In the development phase of the egg incubator device, identifying the target consumers is a critical step to ensure alignment with user expectations and functional requirements. This identification process was undertaken by organizing a FGD involving several potential users, aiming to explore and capture their specific needs and preferences (Table 1). The collected insights were then structured and documented in the form of a customer needs table, serving as a fundamental reference for the design and development stages.

Table 1. Customer needs

Need	Imp
Function	5
Maintenance	3
Ease of operation	4
Backup power supply	3
Design	1
Capacity	2

In designing and fabricating the incubator, the applied technical specifications must be aligned with user requirements to ensure functionality and relevance. Table 2 presents a detailed overview of these technical specifications.

Table 2. Technical specific

Needs	Metric	Imp	Units
1,3,4	Success rate	5	percentage
1,5	The incubator is equipped with a backup power system	4	watt
2,6	Constructed using durable and robust materials	3	mm
1,3	The incubator is equipped with an automated water supply system	4	volt
1,6,7	Egg capacity	3	buah
6	Dimensions	2	cm
2,6	Designed for ease of maintenance	1	months

3.3 Design concept selection

Following the analysis of the collected data, three design alternatives were evaluated (as seen in Table 3), with concept 3 emerging as the top-rated option, attaining the highest score (4.31) as it met the key evaluation criteria—particularly the integration of a solar panel-based backup power solution.

Table 3. Concept criteria

Concept evaluation criteria	Alternative designs		
	1	2	3
Function	+	+	+
Maintenance	+	+	+
Ease of operation	0	0	+
Backup power supply	-	-	+
Design	+	-	-
Capacity	+	+	+
PLUS (+)	4	3	5
SAME (0)	1	1	0
MINUS (-)	1	2	1
NET	3	1	4
RANK	2	3	1
CONTINUE?	Yes	No	Yes

Table 3 presents the process of concept selection, in which three alternative designs were systematically assessed based on key criteria derived from consumer requirements. The evaluation applied a simple scoring system: a '+' indicated performance better than the baseline (concept 1), a '0' indicated no difference, and a '–' indicated lower performance. Among the alternatives, concept 3 achieved the highest net score of 4, largely because it was the only design incorporating a backup power supply—a feature identified during the FGD as a critical need. On this basis, concept 3 was chosen for prototyping and subsequent development.

3.4 Evaluation of solar power and battery capacity requirements

To ensure continuity during outages, the calculations were performed: (1) Load consumption: 19 W × 4 hours = 76 Wh; (2) solar panel energy: 60 W × 5 charging hours = 300 Wh/days; (3) solar panel energy: 12 V×12 Ah = 144 Wh, 144 Wh ÷ 19 W ≈ 7 hours.

In order to maintain uninterrupted functionality of the system during potential grid outages, a technical assessment was conducted to evaluate the energy requirements under backup conditions. Based on the analysis, it was determined that the integration of a 60 Wp photovoltaic solar module with a 12 Ah battery storage system is sufficiently capable of sustaining the continuous operation of the incubator unit for a minimum of four hours in the absence of a primary electrical supply. This finding confirms the reliability of the proposed off-grid power configuration in ensuring short-term autonomy for critical biomedical equipment during emergency scenarios.

3.5 Radiation heat transfer analysis

To maintain operational continuity in the event of a power outage, a series of thermal radiation transfer calculations was performed. The analysis revealed that the average radiative heat power varied slightly between daytime and nighttime across four experimental batches. Specifically, batch 1 recorded 53.52 W during the day and 52.556 W at night; batch 2, 53.568 W and 52.522 W; batch 3, 53.583 W and 52.522 W; and batch 4, 53.571 W and 52.509 W, respectively. These marginal differences are likely influenced by variations in ambient environmental conditions. A comparative diagram illustrating radiative heat transfer measurements conducted during daytime and nighttime trials is presented below to support these findings.

Fig. 11 and Fig. 12 present the radiative power recorded during both daytime and nighttime across four experimental batches. The results indicate that the system maintained a stable thermal output, reflecting consistent heat generation. A minor reduction observed at night can be linked to lower ambient temperatures, which required the heating element to operate more efficiently in order to sustain the target setpoint. These consistent patterns demonstrate the effective role of the thermostat and DC fan in ensuring uniform heat regulation within the incubator.

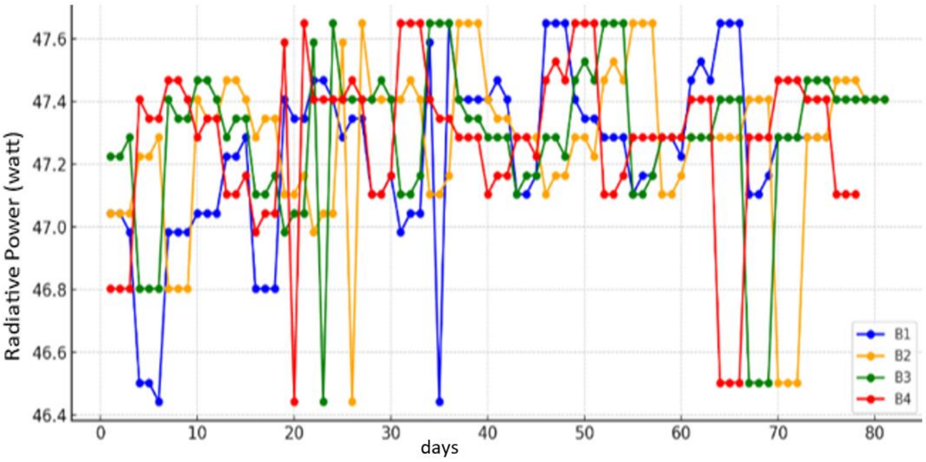

Fig. 11. Radiative power graph–daytime condition.

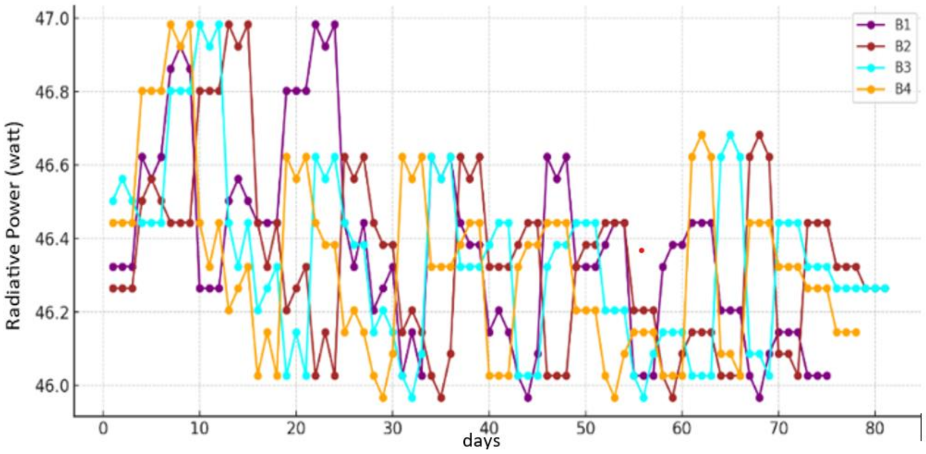

Fig. 12. Radiative power graph–nighttime condition.

3.6 Evaluation of the performance of the solar panel backup power system

To maintain operational continuity during possible power interruptions, appropriate calculations were performed to ensure system reliability. Observations from four separate experimental batches consistently demonstrated a 100% hatching success rate using the automated racking system. This consistent outcome provides strong evidence of the system's effectiveness in creating and sustaining ideal environmental conditions for embryo development, thereby confirming its functional stability and dependable performance under controlled conditions.

Fig. 13 illustrates the gradual decline of battery voltage during operation without charging, dropping from 13.75 V at full capacity to 11.8 V over a span of roughly seven hours. This finding confirms the estimated backup duration. In contrast, Fig. 14 depicts the recharging process, where the voltage rises from 11.8 V to 13.75 V within approximately five hours of direct sunlight exposure. These results highlight the solar panel's effectiveness in fully restoring the battery each day, thereby ensuring the system remains ready to operate reliably during potential power outages.

3.7 Hatching success rate evaluation

To ensure operational continuity during potential shutdown events, a set of engineering calculations was conducted, with the process illustrated in Fig. 15. These calculations focus specifically on the radiative mode of heat transfer, which plays a critical role in maintaining thermal equilibrium under non-standard operating conditions.

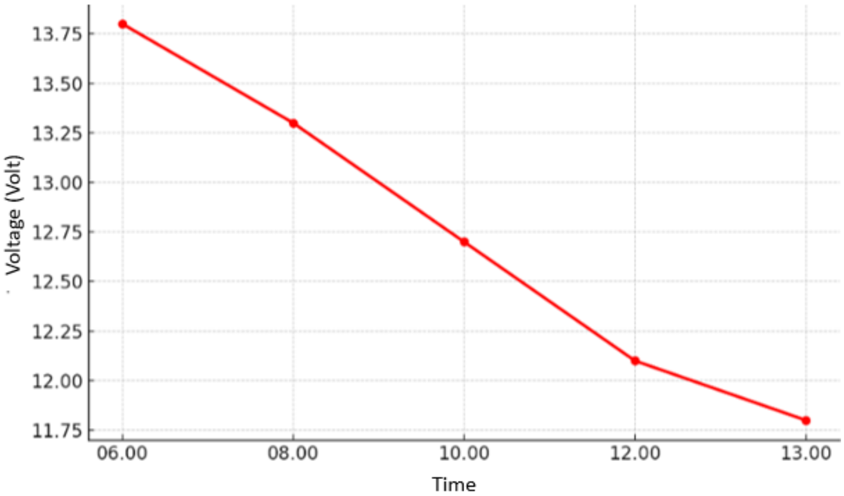

Fig. 13. Voltage during operation.

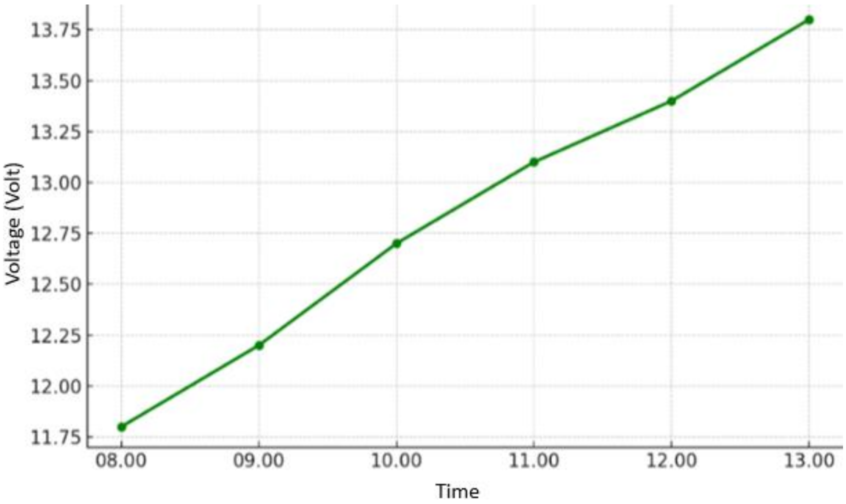

Fig. 14. Voltage during charging.

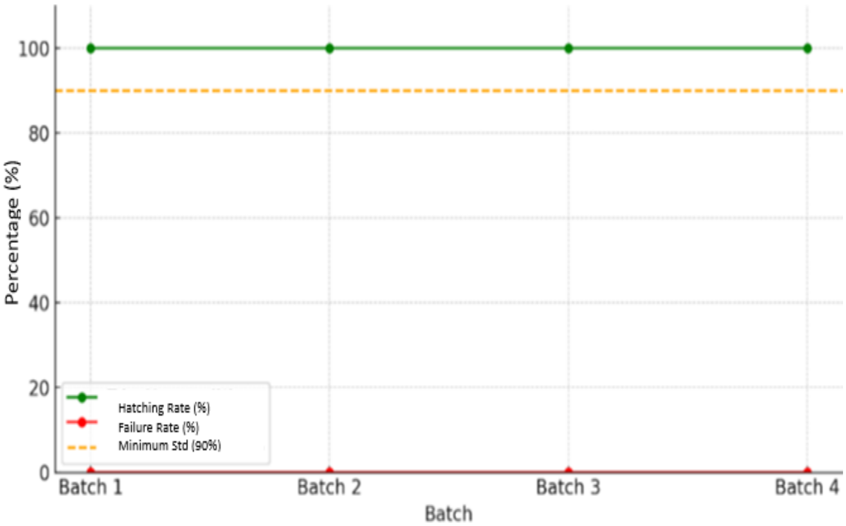

Fig. 15. Hatchability rate graph.

3.8 Comparative analysis with previous research

The 100% hatching rate achieved in this study marks a notable advancement compared with conventional practices and previously reported incubator designs. Nugroho and Sari (2020) documented that a standard incubator without a backup power supply achieved only a 75% hatching rate under stable grid conditions, with performance dropping considerably during outages [17]. Similarly, another study on incubators that relied on manual egg turning reported an average success rate of about 80%, largely due to uneven heat distribution [18]. The improved performance of the proposed system arises from the combined effect of an automated sliding rack, which ensures uniform thermal distribution, and a solar-powered backup that provides operational reliability. Systematically developed through the QFD method to align with farmer requirements, this dual-feature design successfully addresses two of the most frequent limitations in small-scale incubation systems.

4 Conclusions

This study confirms that applying the QFD framework, supported by the HOQ, effectively translated the key requirements of free-range poultry farmers into clear technical specifications. The automatic sliding rack improved heat distribution, keeping incubation temperatures steady within the ideal 37–40°C range. In addition, the integration of a 60 Wp solar panel with a 12 V-12 Ah battery provided dependable backup power for up to seven hours, ensuring continuous operation during outages. Across four independent trials, the system consistently achieved a 100% hatching rate (exceeding the 65–75% for conventional incubators) and outperforming incubators lacking automated turning or backup power. This hybrid design, combining renewable energy with automation, not only boosts energy efficiency and hatchability but also offers a sustainable and practical solution to support local free-range poultry farming.

Acknowledgements

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