Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 10, No. 1, 417-429
2026
Publisher: Learning Gate
DOI: 10.55214/2576-8484.v10i1.11618

Development of IoT-based black soldier fly egg incubation system

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Abstract: This article presents the development of an Internet of Things (IoT)-connected smart Black Soldier Fly (BSF) egg incubator designed to increase hatching efficiency and reduce manual labor. The system automates the control of temperature, humidity, and air circulation, crucial factors influencing hatching rates and larval growth. By leveraging IoT technology, the system enables remote monitoring and control of environmental conditions through a digital platform, thus minimizing errors from manual adjustments and enhancing production efficiency. The results indicate that the IoT egg incubator can achieve a high hatching rate of up to 99% under optimal conditions (temperature: 25–29°C, relative humidity: 51–70%), while also reducing incubation time compared to hatching at ambient temperature. Additionally, the system monitors resource and energy consumption by automatically adjusting environmental conditions, thereby supporting sustainable agricultural practices. In summary, this newly developed IoT egg incubator is an effective tool for BSF breeding, with the potential to transform BSF agriculture by increasing production efficiency, lowering costs, and promoting sustainability. This technology is particularly suitable for small and medium-sized farms, enabling farmers to scale up BSF production to meet the growing demand for alternative protein sources.
Keywords: *Alternative protein, Black soldier fly larvae, Insect rearing, Internet of Things, Smart agriculture.*

1. Introduction

The demand for insects as a high-quality protein source in animal feed is on the rise [1]. Larvae of the Black Soldier Fly (BSF), scientific name *Hermetia illucens* L. (Diptera: Stratiomyidae), have gained recognition as a valuable source of protein, fat, and vitamins for animal feed [2-4]. Recently, the Association of American Feed Control Officials authorized the use of whole BSF larvae as feed for farmed fish in the U.S., marking the first approval of insect-based animal feed in the country [5]. Additionally, fat from the larvae can be extracted for biodiesel production [6, 7], while the chitin and its derivatives are used in pharmaceuticals and medicine [8], and industries such as food processing, packaging, cosmetics, and agriculture [9]. Furthermore, the global BSF insect market is experiencing rapid growth, with its market value projected to reach $3.96 billion by 2033, growing at a 31% compound annual growth rate (CAGR) from 2022 to 2033. The market volume is expected to increase to 36.9% CAGR, reaching 8,003.7 thousand tons by 2033 [10]. This growth is driven by 1) rising demand for alternative proteins in animal feed and aquaculture, 2) increasing costs of traditional raw materials like fishmeal and soybeans, and 3) government support for insect-based proteins in animal feed [10].

At present, BSF farming in Thailand relies primarily on manual labor. Rearing and managing these larvae require significant time and effort, as farmers must monitor every stage of the process closely, from feeding to maintaining optimal environmental conditions. As a result, increasing production capacity to meet the growing market demand has become essential, given the rapid expansion of the industry. Key factors directly affecting BSF egg hatching include temperature, humidity, and optimal

History: Received: 11 November 2025; Revised: 17 December 2025; Accepted: 22 December 2025; Published: 1 January 2026
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environmental conditions, which significantly influence hatching efficiency [11, 12]. Multiple empirical studies have shown that environmental variables, especially temperature [13], light intensity [14], and photoperiod [15], significantly influence the reproductive performance of adult BSF. Proper modulation of these parameters in a controlled indoor farming environment can reduce the pre-oviposition period and enhance female fecundity.

One study developed an automated incubator for rearing BSF larvae by demonstrating its effectiveness in maintaining optimal moisture and temperature conditions for larval growth. The system successfully facilitated larval development to a harvestable size while minimizing labor and energy use [16]. Though the incubator is automated, it cannot be remotely controlled. Currently, IoT technology plays an increasingly significant role in smart farming by enhancing the efficiency of agricultural production management, improving product quality, and reducing production costs [17]. The use of IoT realizes remote monitoring and control of BSF larvae rearing [18]. While the processes of mating and egg-laying can be manipulated by factors like light and temperature [19, 20], achieving optimal egg production (high output with minimal stress and energy expenditure) requires a carefully planned and controlled approach. Therefore, integrating IoT technology into the incubation process is crucial for improving efficiency and maximizing hatching rates in order to meet established standards. This technological advancement will support higher volumes of BSF production and ensure a sustainable supply that aligns with market demands. The study of agricultural technology, particularly in the breeding of BSF, has gained significant attention as it has the potential to serve as a sustainable source of animal feed or organic fertilizer. Egg and larval production frequently limit the maximum number of organisms raised at a given facility [17].

The automation is introduced to the BSF rearing to increase production efficiency. This paper introduces an IoT-based BSF egg incubation system, which will be referred to as the BSF egg incubator hereinafter. The following are the novel features of the proposed system. Firstly, IoT technology is used in the egg incubation system, unlike previous developments that did not use IoT technology or focused on larval rearing. The IoT technology enables remote monitoring and control of key parameters in BSF egg incubation, including temperature and relative humidity. Remote monitoring and control can be performed through a mobile telephone. Secondly, the system enhances scalability by efficiently expanding the number of eggs to support industrial-level egg and larval production. Thirdly, the usefulness in precision agriculture is provided by the proposed system. This feature is manifested through the experimental use of the proposed BSF egg incubator, where a good hatching rate can be obtained by selecting proper incubation parameters. Fourthly, an economic analysis is provided to compare the case of the BSF egg incubator and the natural incubation method.

The structure of the paper is as follows. After this section, the BSF egg incubator is described. Then the experiment and results are demonstrated. The economic analysis is presented later. The conclusion is given at the end.

2. Materials and Methods

2.1. BSF Egg Incubator Structure

The prototype was created using the 3D Viewer program, followed by research and reference collection on IoT systems to support implementation in measurement and data processing. The egg incubator operates through both hardware and software components. The hardware system consists of four lights, two ventilator fans, and three shelves, while the software system was then installed along with the necessary IoT devices and sensors, and configured to control electronic components for measuring temperature and humidity, and activating lights to raise temperature via a widget in a cloud server, and then visualized on a web platform or mobile device (Figure 1).

DOI: 10.55214/2576-8484.v10i1.11618

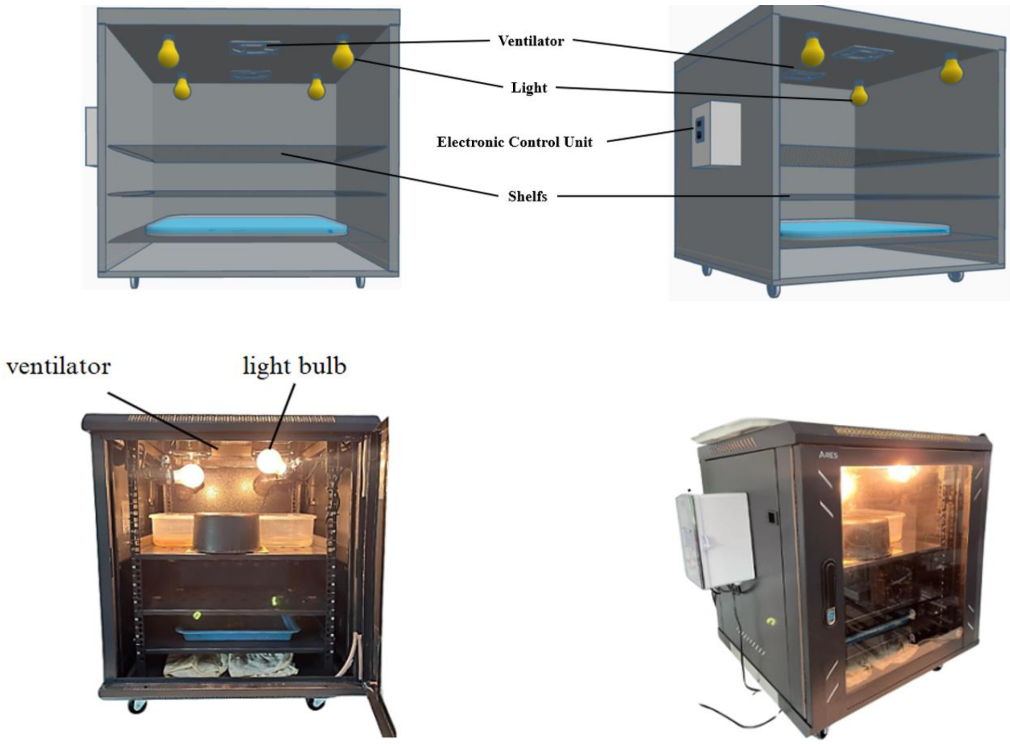

Figure 1.
IoT egg incubator structure.

2.2. Main Components of BSF Egg Incubator (Figure 2):

a) *ESP32*: This serves as the main microcontroller that controls the operation of the fan and light bulbs through GPIO 14 and GPIO 27, which are connected to relays that turn the cooling fan and heating light on/off based on sensor readings. It connects to a cloud server through open-source firmware to send and receive temperature and humidity data. It also controls the fan and light bulbs remotely via Wi-Fi through the cloud system.

b) *PCA9548A I2C Multiplexer*: This module expands I2C connectivity, thus allowing multiple sensors or I2C devices to be connected within the same system. In this circuit, it connects to the temperature and humidity sensors, as well as the OLED display on the I2C bus.

c) *Temperature and Humidity Sensor*: Each sensor measures the temperature and humidity of the environment and sends the data via the I2C bus to the ESP32 through the PCA9548A for processing. These data are then used to control the operation of the fan and light bulbs.

d) *OLED*: The OLED displays values read from the sensors, such as temperature and humidity. It is connected to the ESP32 through the PCA9548A multiplexer on the I2C bus.

e) *Ventilator and Heating Light Bulb*: The ventilators operate when the temperature exceeds the set value, while the light bulb provides warmth when the temperature is too low. Both are controlled by the ESP32 via relays that manage the power supply (220V AC) to the fan and light bulbs.

f) *Relay*: The relay acts as a switch to turn on/off the high-voltage electrical circuit (220V AC) for the fan and light bulbs, based on commands from the GPIO pins of the ESP32.

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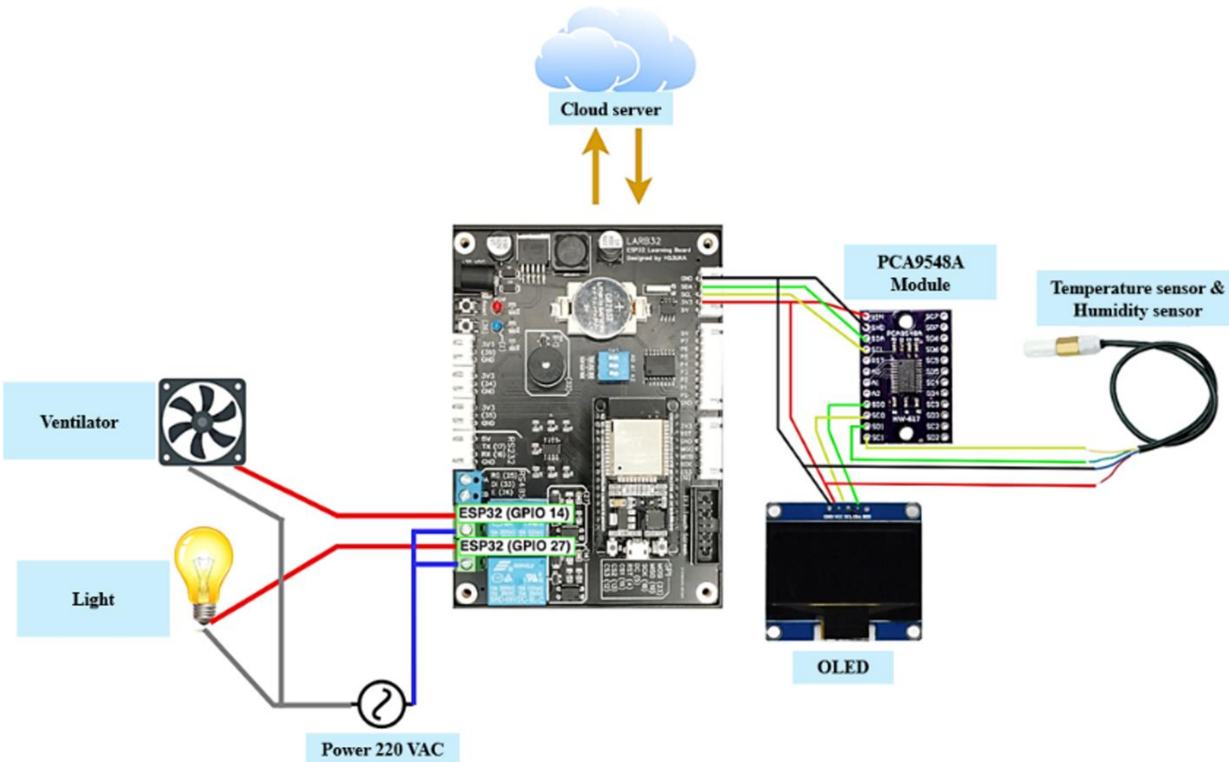

Figure 2.
Circuit diagram for the IoT egg incubator.

2.3. Web User Interface

This interface facilitates real-time data visualization and device control, enabling users to remotely track environmental conditions (e.g., temperature, humidity, light) (Figure 3). Apart from the aforementioned operating unit, including body structure, hardware, and circuit components, the BSF egg incubator also provides a remote monitoring and control unit in the form of a numerical and graphic display (Figures 4 and 5). The real-time and remote communication of the monitoring and control unit is achieved via the web user interface and IoT technology. The display reports the plotting of temperature and relative humidity at each timestamp so that they are continuously monitored. The control allows users to turn the operating unit on and off. Additionally, users can adjust the temperature settings and set the incubation duration as needed. The display also features a countdown timer that shows the remaining incubation time, which aids in efficient planning and management. The operational and fan status both appear on the display, thus facilitating monitoring and providing precise control of the operating unit.

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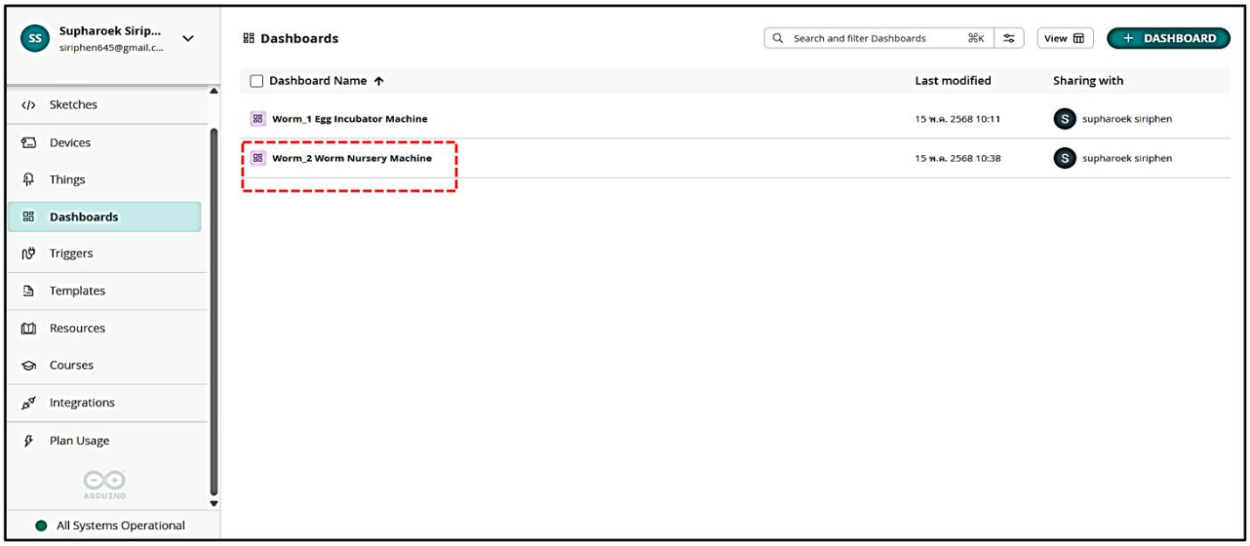

Figure 3.
Web-based interface for tracking and controlling operations.

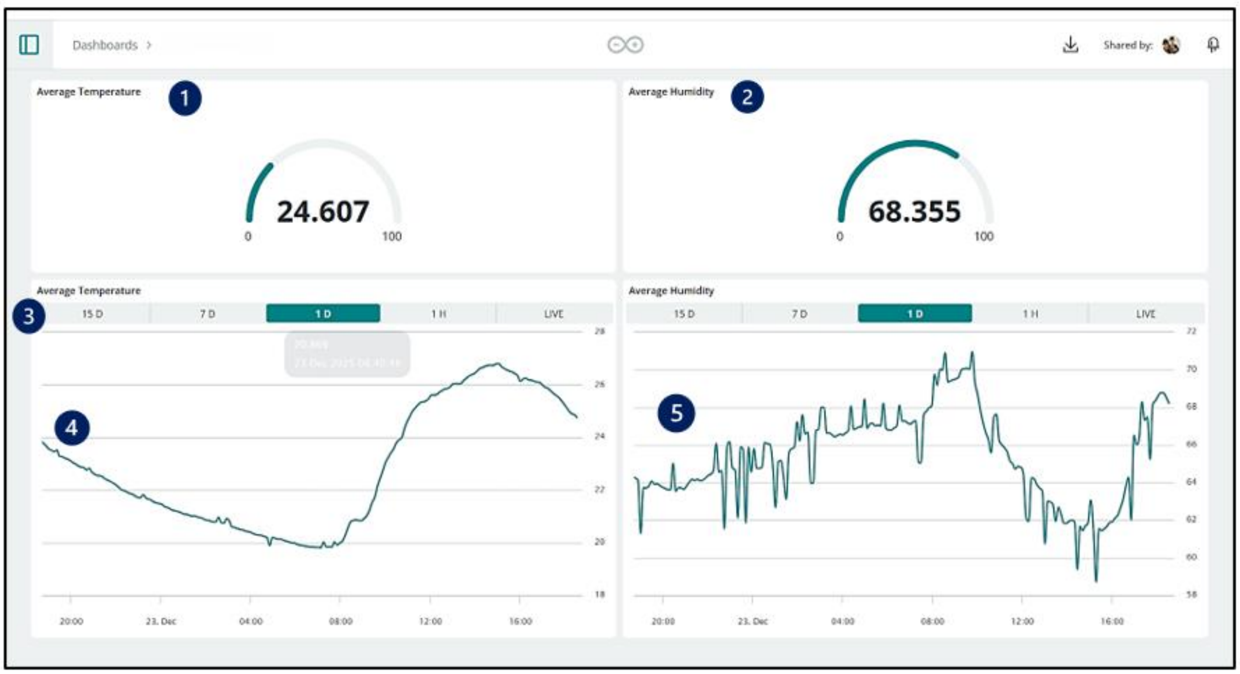

Figure 4.
Web user interface for real-time and remote monitoring and control of the BSF egg incubator.

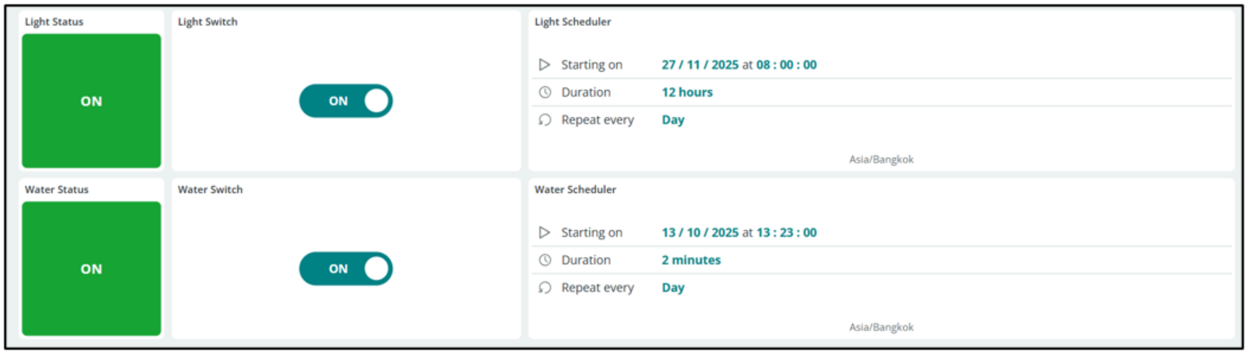

Figure 5.
BSF Egg Incubator Dashboard: Real-time Remote Monitoring (Green Indicators = Normal Operation).

2.4. Operation of BSF Egg Incubator

The ESP32 system begins by connecting to a Wi-Fi network to facilitate data transmission to and from a cloud server. It then configures the I2C connection via the PCA9548A multiplexer, enabling it to read data from multiple sensors. The ESP32 reads temperature and humidity values from sensors connected through I2C. These data are displayed on an OLED screen and transmitted to the cloud server via https://app.arduino.cc/dashboards. This setup allows for remote monitoring and control over the internet through a web user interface. The system continuously monitors whether the recorded temperature or relative humidity exceeds predefined thresholds. If the values remain within acceptable limits, the system loops back to read sensor data again. However, if the values surpass the thresholds, the system activates a relay to control the fan and light, adjusting temperature and humidity to maintain desired levels. After making adjustments, the system continuously loops back to monitor and control the environment in real-time (Figure 6).

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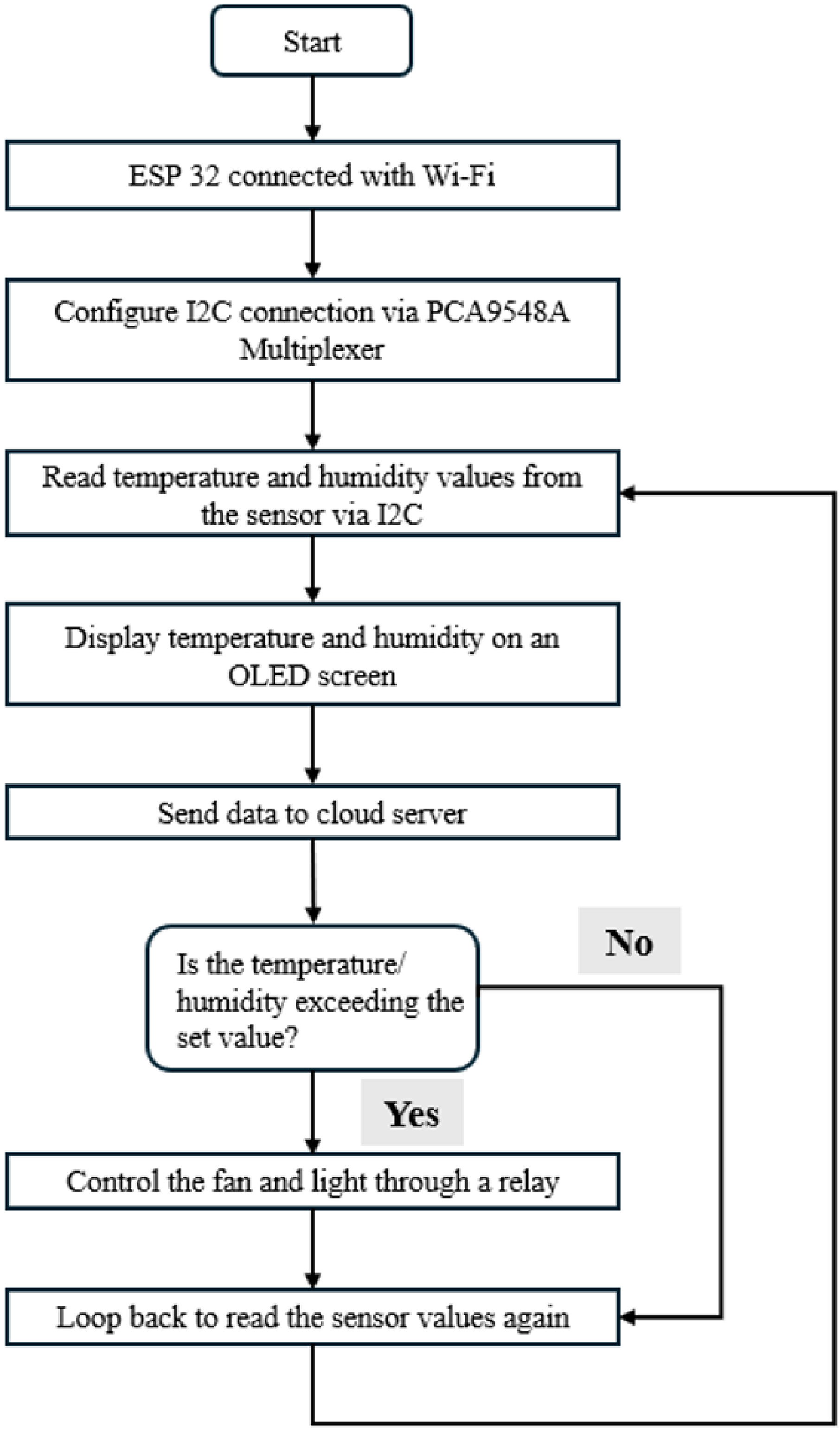

Figure 6.
Flowchart of the operation for the Egg Incubator.

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2.5. Economic Cost Analysis

An economic analysis was conducted to evaluate the operational cost-efficiency of an IoT-based BSF egg incubator system in comparison to a manually controlled system. The assessment was based on annualized fixed and variable costs, energy consumption, software development expenses, and production output in terms of the number of larvae successfully hatched per year.

2.5.1. Cost Components

The total cost was categorized into three main components: (1) fixed capital costs, (2) variable operating costs, and (3) software and IoT system development costs.

- Fixed Costs: These include the initial investment in the IoT controller (ESP32), sensors (DHT22), relay modules, heating and lighting units (infrared bulbs), structural casing, and wiring components. Depreciation is calculated using a straight-line method over the expected lifespan of each component (1–5 years), resulting in an annualized fixed cost.

2.5.2. Annual Depreciation Total Cost/Useful Life (Years)

- Variable Costs: Variable expenses include annual electricity costs calculated from daily energy usage in both standby and active heating modes (20 h/day and 4 h/day, respectively), maintenance and component replacement (e.g., light bulbs, sensors), and labor associated with monitoring the system. Electricity prices are based on an average rate of 4 THB/kWh.
- Software and IoT Development Costs: Development costs included web-based dashboard programming, hosting, API services, and cloud platform subscriptions. Software-related expenses were amortized over their estimated lifespan (1–5 years).

2.5.3. Performance Metrics

To assess economic viability, the total cost per year was divided by the estimated number of larvae hatched annually, which was based on:

- Incubation tray capacity: 30 million eggs per cycle
- Hatching rate: 70–80% under IoT control
- Operating frequency: 2 cycles per week × 4 weeks × 12 months = 96 cycles/year
- Total hatched larvae (IoT system): approximately 2.016 billion larvae/year

For the manual system, labor costs (2 workers/day), identical hardware components (except automation), and a lower hatching rate (60%) were considered.

3. Biological Egg Incubation Experiment

3.1. Experiment Description

BSF eggs were obtained from the "BSF Breeding Prototype Greenhouse" at the Mae Hia Agricultural Research and Training Center, Chiang Mai University, Thailand. The eggs used in this study were collected from female breeders that had laid them within 24 hours. The collected eggs were selected carefully by gently picking up 100 eggs per replicate with a No. 0 brush. The experiment was divided into two groups: 1) eggs incubated in a BSF egg incubator, with temperatures set at 25, 27, 29, and 30 °C; humidity maintained at 50–60% RH, and 2) eggs incubated under natural conditions. Both experimental setups were conducted simultaneously. Each treatment included three replicates per condition. The percentage of eggs that hatched and the time required for egg hatching were recorded. The hatching rate was calculated using the following formula:

Hatching rate (%) = (Number of first instar larvae hatched /Number of eggs at the start) × 100

3.2. Statistical Analysis

Data analysis focused on the percentage of egg hatching and the time required for hatching. A two-factor analysis of variance (ANOVA) was applied, and a one-way ANOVA with post-hoc Tukey HSD

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was used to detect differences among incubation temperatures and humidity levels. All statistical analyses were performed using SPSS version 28.0 (IBM SPSS Statistics®, SPSS Inc., Chicago, IL, USA).

3.3. Experimental Results
3.3.1. Effects of Incubation Temperature on Hatching Rate

The experiment investigated the influence of incubation temperature on the hatching rate and incubation period of Hermetia illucens eggs under five temperature conditions (17, 25, 27, 29, and 30 °C). Each temperature group was replicated three times.

3.1.2. Hatching Rate

The hatching rate was significantly affected by incubation temperature (ANOVA: $F(4,10) = 47.71$, $p < 0.001$). Tukey's HSD post hoc test indicated that hatching rates at 25 °C, 27 °C, and 29 °C were significantly higher than at 17 °C (mean difference = 2.19–2.42%, $p < 0.001$). Additionally, the rate at 30 °C was significantly lower than that at 25–29 °C ($p < 0.01$). However, there were no statistically significant differences among the temperatures of 25, 27, and 29 °C ($p > 0.05$), indicating a plateau of optimal hatching efficiency within this range. The highest average hatching rate (99.33%) was recorded consistently across 25–29 °C, while the lowest (97.00%) occurred at 17 °C.

3.1.3. Incubation Period

Incubation temperature showed a highly significant effect on the duration of larval development (ANOVA: $F(4,10) = 5024.69$, $p < 0.001$). Tukey's HSD test revealed significant reductions in incubation time as temperature increased. The mean incubation period at 30 °C (26.0 h) was markedly shorter than all other conditions, with the longest period observed at 17 °C (71.67 h). Significant differences ($p < 0.001$) were also observed between all adjacent temperature groups except between 25 °C and 27 °C, where no statistical difference was found ($p = 0.074$).
The experimental results are shown in Table 1.

Table 1.
Hatching rate and incubation period at various temperatures under ambient temperature conditions (natural incubation) and in a BSF egg incubator.

Temperature	Ambient temp. (16-18 °C)	25 °C	27°C	29 °C	30 °C	F-value	*p*-value
Hatching rate (%)	97±0.67	99.33±0.67	99.33±0.33	99.33±0.33	98.33±0.44	47.71	0.000002***
Incubation period (hr.)	71.67	67.0	66.0	63.0	26.0	5024.29	<0.00000000001***

Note: *** Significant differences ($p < 0.001$).

Figure 7 demonstrates that under ambient conditions (16–18 °C), the incubation period was the longest at approximately 2.99 days. As the temperature increased, the incubation time gradually decreased to 2.79 days at 25 °C, 2.75 days at 27 °C, and 2.63 days at 29 °C. The shortest incubation period (1.08 days) was observed at 30 °C, indicating that higher temperatures significantly accelerated embryonic development. These results suggest a strong inverse relationship between temperature and incubation duration, with optimal hatching occurring under warmer conditions around 30 °C.

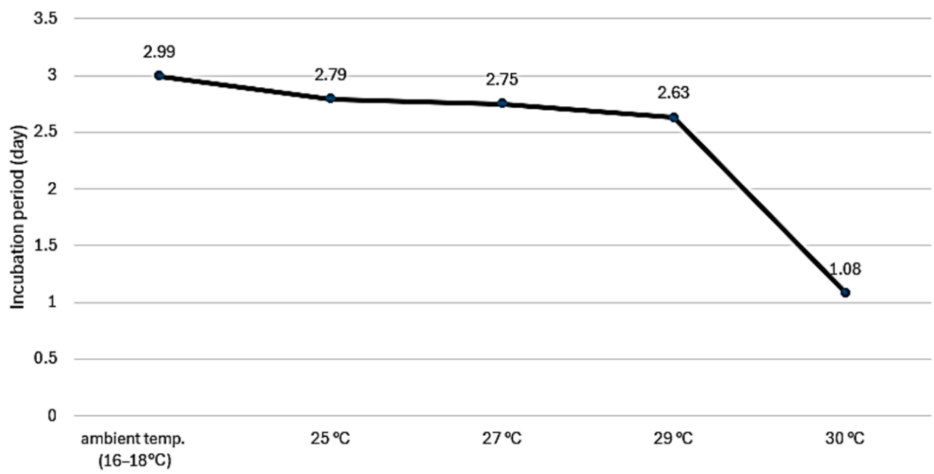

Figure 7.
The effects of temperature on the incubation time.

4. Economic Analysis

As shown in Table 2, the total fixed cost of the IoT-based incubation system was 2,634 THB/year, calculated via straight-line depreciation. The main contributors were infrared bulbs (1,200 THB/year) and the enclosure frame (600 THB/year), followed by other electronic components such as the controller, sensors, and wiring.

Table 2.
Breakdown of Fixed Costs and Annual Depreciation of Components Used in the IoT-Based BSF Egg Incubation System

Item	Total Cost (THB)	Useful Life (years)	Annual Depreciation (THB/year)
IoT Controller (ESP32/Arduino)	500	3	167
Sensor (DHT22, etc.)	300	3	100
Heater + Fan + Relay Module	1,200	3	400
Infrared Bulbs (4 bulbs, 100W)	1,200	1	1,200
Frame/Enclosure	3,000	5	600
Wiring, Adapter, etc.	500	3	167
Total Annual Fixed Cost			2,634 THB/year

Table 3 presents the annual cost comparison between IoT-based and manual BSF egg incubation systems. The total annual operating cost of the IoT-based system was THB 12,983.6, significantly lower than the manual system, which incurred THB 243,649.6 per year. The primary cost drivers for the manual system were labor (THB 240,000/year) and higher maintenance (THB 1,000/year), whereas the IoT-based system involved modest labor (THB 3,000/year), lower maintenance (THB 500/year), and additional software-related expenses (THB 4,200/year). Despite including hardware depreciation and digital services, the IoT system maintained a cost advantage by reducing reliance on manual labor and enabling automation.

ISSN: 2576-8484
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Table 3.
Comparative annual cost structure of IoT-based and manual BSF Egg Incubation systems.

Cost Category	Item Description	IoT-Based System (THB/year)	Manual System (THB/year)
1. Fixed Costs	Hardware depreciation (controller, sensors, etc.)	2,634	–
2. Variable Costs	Electricity (1.84 kWh/day × 365 × 4 THB/kWh)	2,649.6	2,649.6
	Maintenance and component replacement	500	1,000
	Labor	3,000 (approx. 250 THB/month)	240,000 (2 workers × 10,000 THB/month × 12 months)
3. Software & IoT Services	Web/mobile app development (amortized 5 years) - 2,000 THB	4,200	–
	Cloud services - 1200 THB		
	Hosting and APIs – 1,000 THB		
Total Annual Cost		12,983.6	243,649.6

5. Discussion

This study confirms that incubation temperature exerts a significant influence on both the hatching rate and incubation period of BSF eggs. These findings are consistent with previous research, which has highlighted the strong relationship between temperature and developmental performance in Dipteran species.

5.1. Comparison with Previous Studies on Thermal Thresholds

These results are in agreement with the findings of Chia et al. [13], who reported that hatching success of BSF eggs significantly declined below 15 °C and above 37 °C, with optimal hatching performance occurring around 30 °C. Similarly, previous studies emphasized that 25–30 °C is the ideal thermal range for maximizing developmental rates, survivability, and larval yield [3, 21]. These align closely with our data, which demonstrated the highest hatching rates (≥ 99%) within 25–29 °C, with a slight but statistically significant decrease at 30 °C.

5.2. Incubation Period and Developmental Acceleration

The reduction in incubation period with increased temperature is well supported in the literature. Qomi et al. [22] found that the egg development duration decreased from 9 days at 20 °C to only 4 days at 30 °C. This trend aligns with our findings, where incubation time decreased from 71.67 hours at 17 °C to 26 hours at 30 °C. These outcomes are consistent with the Q10 principle in poikilothermic organisms, where metabolic rates approximately double with every 10 °C increase, within physiological limits.

5.3. Implications for IoT-Based System Design

The temperature range of 27–29 °C, identified in this study as optimal, is particularly suitable for automation using IoT-based incubators. Real-time temperature regulation within this range ensures high larval yield and reduced cycle time, increasing batch turnover in commercial hatchery operations. Moreover, unlike manual systems that are susceptible to human error and inconsistent environmental conditions, IoT systems offer greater control, precision, scalability, and cost efficiency as supported by our economic analysis.

6. Conclusions

The prototype incubator designed and tested in this study was successful in improving the hatching efficiency of BSF eggs. The results showed that using the IoT Egg Incubator led to a higher hatching rate and a shorter incubation period compared to hatching under ambient temperature conditions. In practical applications, these insights can be utilized in large-scale insect farming and controlled breeding programs, particularly for species used in sustainable agriculture, biotechnology, and waste management. The ability to monitor incubation conditions through precise temperature and humidity control can enhance productivity, reduce energy consumption, and improve overall efficiency in insect rearing systems. Future studies should further investigate the effects of microclimatic variations and develop adaptive incubation technologies to ensure consistency and scalability in mass insect production.

Funding:

The authors wish to thank the National Research Council of Thailand, grant number N24A671196, for its support.

Institutional Review Board Statement:

The protocol of this study was approved by the Research Ethics Committee (Protocol number 2567/AG-003), Laboratory Animal Center, Chiang Mai University.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Acknowledgments:

The authors wish to thank the BSF Breeding Prototype Greenhouse and the Mae Hia Agricultural Research and Training Center, Chiang Mai University, Thailand, for providing a laboratory room.

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