Development of an Automated Incubator System for Efficient Breeding of Darkling Beetle

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***Abstract*—This study evaluates the impact of temperature and humidity on the hatch quantity of Superworms (Zophobas morio) to assess the potential of Internet of Things (IoT)-enabled automated incubation system for efficient breeding. Superworms are valuable for waste management, bioconversion, and as a nutritious food source, but their reproduction declines under unfavorable environmental conditions. An Internet of Things (IoT)-enabled automated incubation system was developed to maintain optimal environmental conditions (24.5°C–29.5°C, 60%-75% humidity) over 31 days. Three trials, each using 30 darkling beetles, were conducted under controlled and uncontrolled conditions (dry and rainy seasons). Hatch quantities were 971, 532, and 917 Superworms for the controlled, dry season, and rainy season environments, respectively. Significant improvement was observed in the controlled environment compared to the dry season, but no significant difference was found compared to the rainy season. These findings demonstrate the efficiency of automated incubation systems for enhancing sustainable Superworm production.**

Keywords—Superworms (Zophobas morio), Darkling beetles, Sustainable production

I. Introduction

Superworms *(Zophobas morio)*, the larval stage of darkling beetles, require specific environmental conditions for optimal growth, survival and reproduction [1]. These insects thrive at temperatures between 21°C and 30°C, prefer darker environments and need adequate moisture [2]. Unlike mealworms, Superworms are larger, more sensitive to storage, and cannot be refrigerated. They are also higher in fiber, calcium, and fat, making them ideal food sources for fish, reptiles, and birds [3]. Despite their potential for animal nutrition and waste management, their seasonal breeding patterns limit production, especially during unfavorable temperature ranges beyond 21°C and 30°C.

In the Philippines, which is characterized by high humidity, significant rainfall, and high temperatures, darkling beetles typically breed during the cool or rainy seasons. However, their breeding process is disrupted during the hot dry season (March to May) [4]. During this period, temperatures exceed the optimal range, hindering egg survival and beetle reproduction, which takes over two months to complete. This creates supply challenges for Superworms during this period.

To address these limitations, this study proposes a cost-effective, IoT-enabled incubator designed to maintain optimal temperature and humidity for breeding darkling beetles during the hot dry season. The research seeks to determine the most effective environmental conditions for maximizing hatch quantity by comparing controlled and uncontrolled environments. This work contributes to improving breeding practices, ensuring a consistent supply, and developing a maintenance control plan based on findings.

II. Methodology

This study employed an experimental approach, specifically design of experiments (DOE), to investigate the influence of temperature and humidity (independent variables) on the hatch quantity of Superworms *(Zophobas morio)* within an artificial darkling beetle breeding incubator. This approach aimed to understand the cause-and-effect relationship between environmental conditions and hatch success, treating the incubator as a black-box system and focusing on its external behavior in response to controlled internal settings.

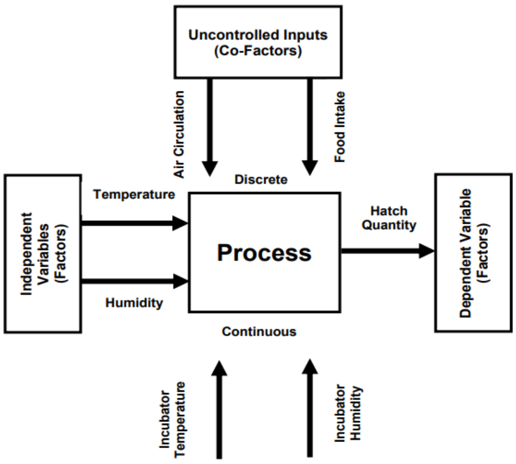

Fig. 1. Black Box Process Schematic Model

Three distinct temperature and humidity settings were tested: 24.5°C to 27.5°C with 60% to 70% humidity, 25.5°C to 28.5°C with 65% to 75% humidity, and 26.5°C to 29.5°C with 60% to 70% humidity. Air circulation was maintained at a constant rate throughout the experiment, while each unique combination of temperature and humidity was considered a separate trial.

The ESP32 microcontroller was equipped with a BME280 sensor that measures the temperature and humidity at predetermined intervals. The microcontroller was programmed to trigger the cooling, heating, and humidification systems based on the recorded data (sensor readings) and the ideal environment conditions of the incubator. These data were published to an MQTT cloud broker in real time, stored in a cloud database, and displayed on a dedicated web application. This continuous monitoring and control loop were automated, resulting in constant and optimal incubation conditions for the darkling beetles.

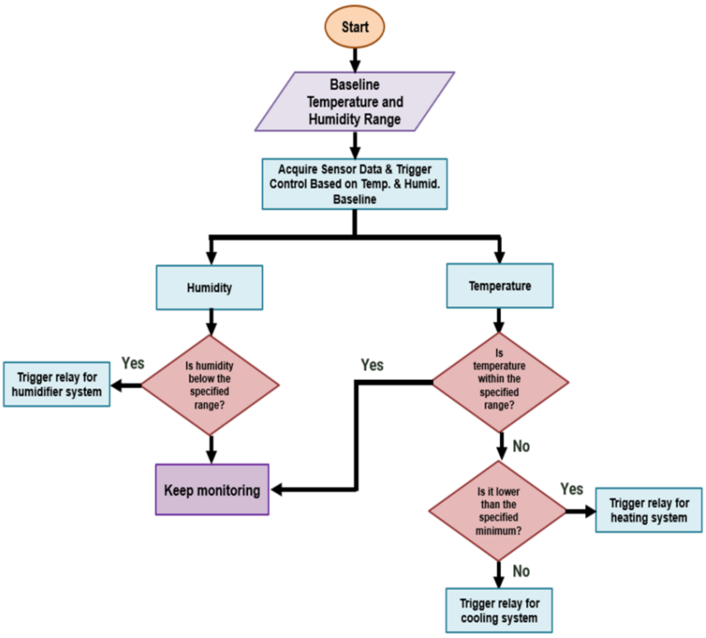

Fig. 2. Flow Chart – Operation of the System

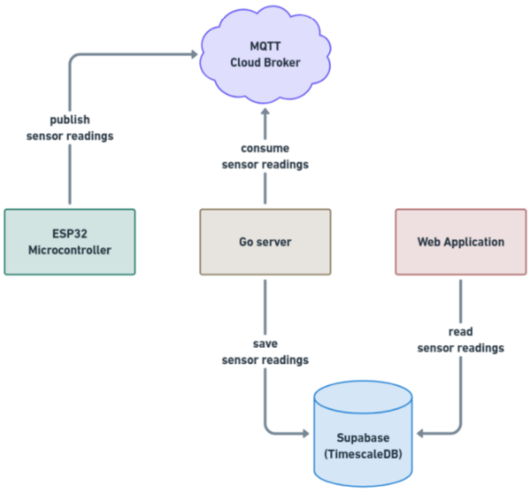

Fig. 3. System Design Overview for the Internet of Things

The darkling beetle population in both controlled and uncontrolled environments was enumerated three weeks and ten days after hatching. This standardized counting procedure was conducted at a fixed time to ensure consistency. The collected data was used to evaluate the incubator system's effectiveness in supporting darkling beetle growth and reproduction. The data on darkling beetle breeding, including hatching egg quantities, were subjected to statistical analysis. Controlled conditions involved varying temperatures and humidity, and constant light sensitivity and air circulation, which were compared to traditional, uncontrolled breeding. The average hatch quantity in each environment was compared to determine the significant difference between automated and manual breeding and to assess the impact of temperature and humidity on beetle breeding. An Independent T-test was used to compare mean hatching quantities between controlled and uncontrolled environments. Mean values represented the average hatch quantity in each environment, while Standard Deviation indicated the data dispersion around the mean.

III. Results and Discussion

This study evaluates the performance of the Automated Incubator System for efficient breeding of darkling beetle based on its capability to regulate temperature and humidity for optimal breeding conditions and its IoT-based monitoring platform. This study also analyzes the hatch quantities under controlled and uncontrolled settings, compares mortality rates across seasons, and evaluates the influence of specific environmental conditions. The findings provide insights into the optimal temperature and humidity ranges necessary for achieving consistent and sustainable breeding conditions.

A. Design, Development, and Implementation of an IoT-Enabled Incubator for Darkling Beetle Breeding

1.) Design of the Automated Incubator System

The automated incubator system was designed using a Black Box Process model, with a focus on regulating temperature and humidity to optimize the hatch quantity of Superworms *(Zophobas morio)*. The main components included a stainless-steel casing, insulation foam for thermal regulation, and designated chambers for darkling beetles. The system featured a structured layout for component placement, ensuring functionality and airflow while accounting for light sensitivity.

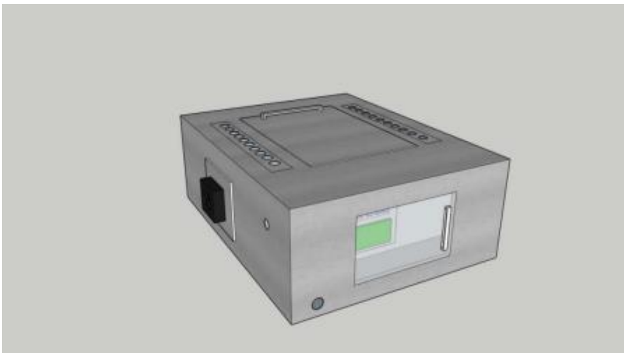

Fig. 4. Exterior Design of the Incubator System

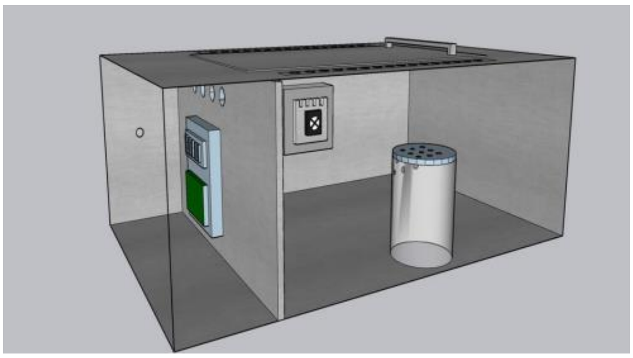

Fig. 5. Interior Design of the Incubator System

2.) Development of the Automated Incubator System

The development phase integrated hardware and software components to monitor and control environmental conditions. An ESP32-WROOM-32 microcontroller was programmed in C++ to operate the relay systems and manage the thermoelectric cooling, ceramic hear lamp, ultrasonic mist maker, and fans. The system utilized BME280 sensor to measure temperature and humidity and employed relays to activate components based on specific requirements. A centralized power supply (24V 10A SMPS) provided power through DC converters, and a real-time IoT-based interface was developed for remote monitoring.

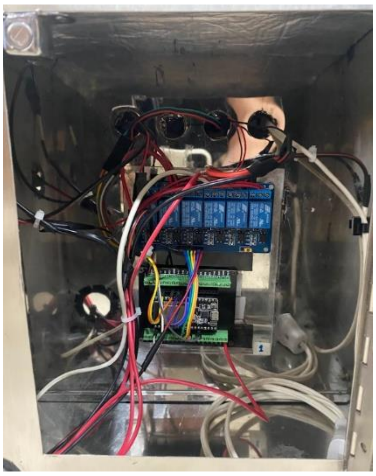

Fig. 6. Internal Setup of the Incubator System

Fig. 7. Interior Setup of the Incubator System

Fig. 8. The Automated Incubator System featuring its centralized 24V 10A SMPS for power distribution

3.) Implementation of the Automated Incubator System

The system was tested with three incubators set at different temperatures and humidity levels: 24.5°C-27.5°C with 60%-70%, 25.5°C-28.5°C with 65%-75%, and 26.5°C-29.5°C with 60%-70%. The final assembly included placing darkling beetles inside the incubators, along with nesting trays and provisions to replicate ideal habitat conditions. The IoT interface displayed real-time environmental data, allowing researchers to remotely monitor and control the incubators to ensure consistent functionality.

Fig. 9. Interior Setup of the Incubator System with Darkling Beetles

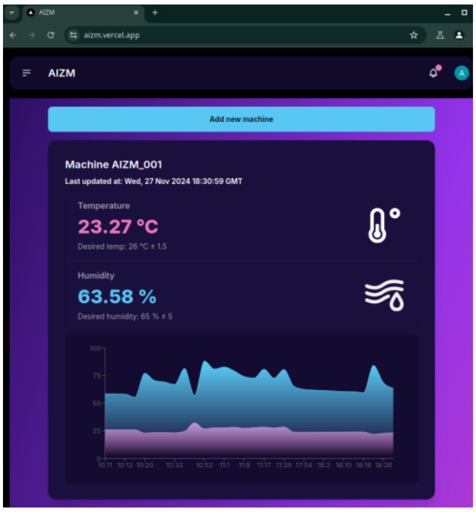

Fig. 10. Preview of the AIZM website

B. Effect of the Temperature and Humidity on the Hatching quantity of Superworms (Zophobas Morio)

The tables below examine the effect of temperature and humidity on the hatching quantity of Superworms (Zophobas morio). Environmental conditions, particularly temperature and humidity, are critical factors influencing the reproductive success and survival rates of Darkling Beetles. By evaluating both controlled and uncontrolled settings, the study provides a clear comparison of how temperature and humidity affect the breeding success of darkling beetles. The findings emphasize the importance of maintaining optimal environmental parameters to achieve sustainable and efficient Superworm production.

1.) *Uncontrolled Environments (Dry and Rainy Seasons)*

TABLE 1. MORTALITY RATE, DEATH COUNT, AND HATCHED EGG COUNT OF DARKLING BEETLES IN UNCONTROLLED (DRY AND RAINY SEASON) ENVIRONMENT

Environment		Number of Darkling Beetles	Number of Deaths	Death Rate (%)	Hatched Eggs
Uncontrolled (DRY SEASON)	Trial #1	30	25	83.33	172
	Trial #2	30	20	66.67	181
	Trial #3	30	23	76.67	179
Uncontrolled (RAINY SEASON)	Trial #1	30	2	6.67	311
	Trial #2	30	4	13.33	305
	Trial #3	30	7	23.33	301

Table 1 shows that during the uncontrolled dry season, mortality rates were high, ranging from 66.67% to 83.33%, with low egg hatch counts of 172 to 181. In contrast, the rainy season exhibited significantly lower mortality rates, ranging from 6.67% to 23.33%, and higher egg hatch counts, ranging from 301 to 311. These results illustrate that cooler temperatures and higher humidity created more favorable conditions for both reproduction and survivability.

2.) *Controlled Environments*

TABLE 2. MORTALITY RATE, DEATH COUNT, AND HATCHED EGG COUNT OF DARKLING BEETLES IN CONTROLLED ENVIRONMENT

Environment		Number of Darkling Beetles	Number of Deaths	Death Rate (%)	Hatched Eggs
Controlled	Temperature: 24.5°C to 27.5°C Humidity: 60%-70%	30	3	10	343
	Temperature: 25.5°C to 28.5°C Humidity: 65%-75%	30	6	20	312
	Temperature: 26.5°C to 29.5°C Humidity: 60%-70%	30	5	16.67	316

Table 2 shows that the optimal breeding conditions were achieved at temperatures of 24.5°C to 27.5°C and humidity levels of 60%-70%, resulting in the lowest mortality rate of 10% and the highest egg hatch count of 343. Higher temperature and humidity ranges increased mortality rates to 16.67% to 20%, with slightly reduced egg hatch counts ranging from 312 to 316.

3.) *IoT-Enabled Incubators*

TABLE 3. INTERNET OF THINGS (IOT)-ENABLED THREE INCUBATORS ACROSS THREE TRIALS AVERAGE TEMPERATURE AND HUMIDITY FOR 3 WEEKS AND 10 DAYS

Incubator	Temperature (°C)	Humidity (%)
AIZM_001	27.50	79.72
AIZM_002	28.33	84.69
AIZM_003	28.56	72.18

Table 3 shows that the IoT-enabled incubators maintained stable temperatures ranging from 27.50°C to 28.56°C, with variable humidity levels ranging from 72.18% to 84.69%. This variability in humidity may influence breeding outcomes despite stable temperature regulation, as moisture is a critical factor in reproductive success.

C. *Significant Difference between Controlled and Uncontrolled Conditions*

The tables below investigate the statistical differences between controlled and uncontrolled environments in the hatching success of Superworms *(Zophobas morio)*. Environmental factors, including temperature and humidity, were analyzed to determine their impact on the survival and reproduction of darkling beetles. Statistical tools, such as t-tests and p-values, were employed to compare hatching outcomes across dry and rainy seasons under uncontrolled conditions and in a controlled environment. The findings highlight the importance of precise environmental control in optimizing breeding success while addressing variability challenges in controlled setups.

1.) *Statistical Analysis of Superworm (Zophobas morio) Counts in Uncontrolled (Rainy Season) and Controlled Environments*

TABLE 4. STATISTICAL ANALYSIS OF SUPERWORM (ZOPHOBAS MORIO) COUNTS IN UNCONTROLLED (RAINY SEASON) AND CONTROLLED ENVIRONMENT

Environment	Mean	Variance	Standard Deviation	t-value	p-value (two-tailed) α=0.05	Deci-sion
Uncontrolled	306	25.333	5.033	-1.772	0.21845	Fail to reject the null hypo-thesis
Controlled	324	284.333	16.862			

Table 4 shows that the mean Superworm *(Zophobas morio)* count was higher in the controlled environment (324) compared to the uncontrolled environment (306), suggesting a slight advantage for breeding under controlled conditions. However, with a p-value of 0.21845, which exceeds the significance level of 0.05, the null hypothesis could not be rejected. This indicates no statistically significance in superworm counts between the two environments during the rainy season. Variance and standard deviation analysis revealed greater variability in the controlled environment (variance = 284.333, standard deviation = 16.862) compared to the uncontrolled environment (variance = 25.333, standard deviation = 5.033).

2.) Statistical Analysis of Superworm (Zophobas morio) Counts in Uncontrolled (Dry Season) and Controlled Environments

TABLE 5. STATISTICAL ANALYSIS OF SUPERWORM (ZOPHOBAS MORIO) COUNTS IN UNCONTROLLED (DRY SEASON) AND CONTROLLED ENVIRONMENT

Environment	Mean	Variance	Standard Deviation	t-value	p-value (two-tailed) α=0.05	Decision
Uncontrolled	177	22.333	4.726	-14.773	0.00474	Reject the null hypothesis
Controlled	324	284.333	16.862			

Table 5 shows that the mean Superworm *(Zophobas morio)* count was significantly higher in the controlled environment (324) compared to the uncontrolled environment (177) during the dry season. With a p-value of 0.00474, which is less than the significance level of 0.05, the null hypothesis was rejected, confirming a statistically significant difference between the two environments. Variance and standard deviation analysis revealed greater variability in the controlled environment (variance = 284.333, standard deviation = 16.862) compared to the uncontrolled environment (variance = 22.333, standard deviation = 4.726), which exhibited more consistent bur lower counts.

D. Maintenance Control based on the results of the study

The maintenance control measures for the incubation system address a variety of potential issues to ensure optimal performance and beetle health. For electrical system or connectivity issues, it is recommended to turn off the system, inspect for damages or loose connections, test with a multimeter, and monitor for anomalies after restarting. Sensor inaccuracies or wiring damage can be mitigated by cleaning, calibrating, and securing sensors weekly to maintain accurate readings. Poor ventilation should be resolved by regularly cleaning fan motors to ensure optimal airflow and temperature control.

To prevent contamination or disease risks from improper food consumption or cleaning, fresh food should be provided every two days, the incubator cleaned regularly, and beetle behavior monitored. Unhygienic or contaminated bedding must be replaced when it becomes dirty, moldy, or excessively wet to maintain a healthy environment. For physical damage or leaks in the incubator affecting its controls, monthly inspections should be conducted to ensure the system’s structural integrity and functionality. Additionally, environmental issues affecting beetles’ survival and reproduction should be addressed by reviewing daily Internet of Things (IoT) system data logs to maintain ideal temperature and humidity conditions.

IV. CONCLUSION

The breeding experiment utilized a Black Box Process model, which included defining objectives, determining variables, designing the system, developing and testing the system, and implementing it. In uncontrolled conditions, high mortality rates were observed, ranging from 66.67% to 83.33% during the dry season and 3.33% to 23.33% during the rainy season, with significantly lower mortality rates recorded in the rainy season. These conditions resulted in Superworm production of 532 and 917, respectively. In contrast, controlled conditions with temperatures maintained at 24.5°C-29.5°C and humidity levels of 60%-75% yielded 971 Superworms, with mortality rates ranging from 10%-20%. The specific range of 24.5°C-27.5°C with humidity levels of 60%-70% setting was identified as the optimal condition. Analysis revealed a significant difference between uncontrolled (dry season) and controlled conditions, while no significant difference was observed between uncontrolled (rainy season) and controlled conditions. Regular maintenance, including sensor calibration, fan cleaning, and electrical system inspection, is essential for consistent breeding success and for mitigating potential issues.

The development of an automated incubator system for the efficient breeding of darkling beetles has been a success, as it has demonstrated its effectiveness in optimizing breeding outcomes under controlled conditions. The incubator system is designed with adaptability and can be used throughout all seasons in the Philippines, providing a sustainable and efficient solution for Superworm production despite variations in environmental conditions.

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