

# Utilization of the Decision Tree Method for pH Monitoring in IoT-Based Black Soldier Fly (*Hermetia Illucens*) Cultivation

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**Abstract**— Organic waste management is a significant challenge in urban areas, and bioconversion using Black Soldier Fly (BSF) larvae has emerged as a promising solution. However, the optimal cultivation process for BSF requires intensive and precise environmental condition monitoring. This research aims to design and implement an Internet of Things (IoT) based monitoring system to optimize the maintenance of BSF larvae by analyzing the influence of environmental variables in real-time. The method involves developing ESP32-based hardware with Temperature (DHT22), Humidity (DHT22), Light Intensity (BH1750), and CO<sub>2</sub> (MQ135) sensors connected to a MySQL database, along with a web interface for visualization. A hybrid prediction model based on a Decision Tree with a k-Nearest Neighbors fallback mechanism was implemented to predict the pH value of the larvae's medium based on sensor data. Testing results show that the designed hardware is highly reliable, with sensor accuracy rates of 98.82% for Temperature, 98.30% for Humidity, and 98.92% for CO<sub>2</sub>. The developed pH prediction model achieved an accuracy of 97.55% with an average error rate of only 2.45%. All system functionalities, from data transmission to web visualization, were proven to be valid and performed as expected. This research successfully demonstrates that an IoT-based monitoring system equipped with a predictive model can be an effective solution for analyzing and optimizing the BSF cultivation environment, thereby supporting a more efficient organic waste bioconversion process.

**Keywords**— Bioconversion, Black Soldier Fly (BSF), Decision Tree, Internet of Things (IoT), Multiparameter Sensor.

## I. INTRODUCTION

As population and economic growth continue, household waste management has become a crucial issue in major Indonesian cities [1]. The largest component of this waste is organic matter, which accounts for approximately 60% of the total volume. Inefficient management of organic waste can trigger various environmental problems, from water and soil pollution to increased greenhouse gas emissions that contribute to climate change [2]. This problem is exacerbated by low public awareness in segregating organic waste, which hinders the recycling process. Furthermore, there are significant technical challenges in converting organic waste into useful products such as compost or biomass [3].

One promising solution for organic waste treatment is bioconversion using the larvae of the black soldier fly (BSF), *Hermetia illucens*. These larvae have a significant capacity to decompose a wide range of organic materials, from food scraps to agricultural waste [4]. The bioconversion process itself is defined as the transformation and decomposition of nutrients in organic waste to produce new protein biomass through the action of microorganisms or insect larvae [5]. Utilizing BSF larvae as bioconversion agents not only drastically reduces waste volume but also yields high-value byproducts such as organic fertilizer and protein-rich animal feed [6]. The protein content in BSF larvae can reach 40-50%, with a fat content of about 29-32%. Due to this nutritional profile, BSF meal has shown the potential to replace fishmeal by up to 100% in broiler chicken feed without negatively affecting nutrient

digestibility, although a 25% substitution level has shown the most optimal results [7]. Moreover, the oil extracted from the maggots contains lauric acid, a valuable component widely used in the cosmetics industry as a moisturizing and cleansing agent [8]. Thus, BSF farming offers a sustainable and economical alternative in the organic waste management cycle. However, despite its potential, the large-scale cultivation and rearing of BSF larvae still face a significant obstacle: it is often labor-intensive, requiring intensive manual intervention [9].

To address this challenge, this research, titled "Utilization of the Decision Tree Method for pH Prediction in IoT-Based Black Soldier Fly (*Hermetia illucens*) Cultivation," proposes an intelligent automation system. An innovative approach is taken wherein pH, a key parameter for successful cultivation, is not measured directly using conventional pH sensors, which are often expensive and require frequent calibration. Instead, the pH value will be predicted based on data from other correlated environmental sensors, such as temperature, humidity, and gas levels (CO<sub>2</sub>). For this prediction task, the Decision Tree method was chosen for its key advantages. First, Decision Trees offer high interpretability [10]; the model generates easily understandable "if-then" logical rules [11], allowing researchers to transparently see how specific combinations of temperature, humidity, and gas affect the acidity (pH) of the medium [12]. This insight is invaluable for understanding the underlying biological decomposition processes [13]. Second, this method can model complex non-linear relationships between environmental variables and pH

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[14], which more accurately reflects the biochemical reality than linear models. Third, Decision Trees are computationally efficient and lightweight [15], making them an ideal choice for implementation on a resource-constrained microcontroller like the Arduino Uno [16], which serves as the brain of this system.

## II. METHOD

This study is an applied experimental research project that aims to develop an IoT-based automatic control system for the optimization of Black Soldier Fly (BSF) cultivation as a solution for organic waste management. The methodology employs an experimental design with a quantitative approach, where the system is engineered to monitor and control crucial environmental variables such as temperature, humidity, and light intensity, specifically for two BSF life stages: the larvae and the adult flies.

The system implements a hybrid control logic. For rapid response, a rule-based control logic is utilized, which automatically activates actuators (e.g., lights or a water pump) when sensors detect that environmental conditions have deviated from predetermined optimal thresholds. In addition, for advanced analysis, a Decision Tree machine learning model is applied. This model functions to predict complex parameters that are difficult to measure in real-time, such as the pH value of the larval medium, based on data from other sensors. The combination of these two mechanisms enables the system not only to perform automatic environmental corrections but also to provide predictive recommendations for manual intervention, thus integrating embedded systems engineering, machine learning, and sustainable waste management.

### A. Research Framework and Workflow

The framework of this research is designed with a systematic and structured workflow, which is divided into two main stages: system development and data implementation & analysis. The objective of this workflow is to build and validate an Internet of Things (IoT)-based automatic control system to optimize the efficiency of the organic waste bioconversion process using Black Soldier Fly (BSF).

The research workflow designed for this study is illustrated in Fig. 1. This research workflow is executed in two main stages: system development and implementation-analysis. The first stage commences with problem identification and a literature review to establish the optimal environmental parameters for BSF larvae and adult flies. This is followed by architectural design, physical prototype development, and iterative functional testing of the hardware until the system is deemed viable.

The second stage begins with the collection of real-time data from the cultivation enclosures using the validated prototype. This data is then used to train and test the Decision Tree machine learning model, which is designed to predict complex parameters such as the medium's pH. The performance of this model is further refined through cycles of testing and retraining. The final research stage involves a quantitative analysis of the control system's overall effectiveness on BSF productivity, culminating in the formulation of conclusions to address the research problems.

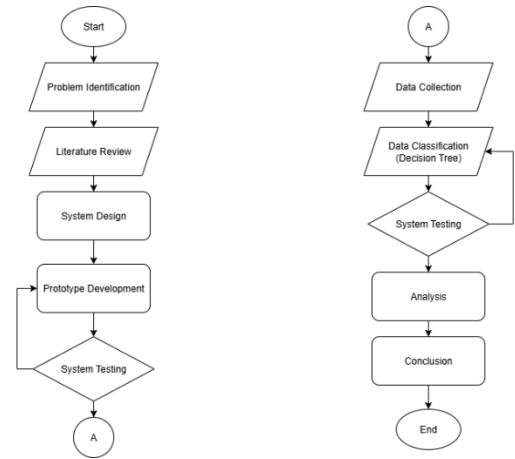


Figure 1. Research stages

### B. Data Collection and Analysis

Environmental data from the BSF cultivation enclosures is collected in real-time using an IoT sensor system. Prior to analysis, this raw data undergoes a pre-processing stage that includes normalization to balance the value scales between the different sensor variables. Data analysis to predict the pH value of the larval medium is conducted using a hybrid model.

The primary model is a Decision Tree Regression, which is trained to generate a set of prediction rules. For data instances that do not match these rules, the system employs a k-Nearest Neighbors (k-NN) fallback mechanism with  $k=1$ . This mechanism functions by calculating the Normalized Euclidean Distance to find the single closest historical data point as the basis for prediction, ensuring that each sensor variable (Temperature, Humidity,  $\text{CO}_2$ ) contributes fairly. This hybrid approach was selected to combine the interpretability of the Decision Tree's rules with the flexibility of k-NN in handling unique data instances. The distance calculation is performed using the following Normalized Euclidean Distance Equation (1):

$$Distance = \sqrt{\left(\frac{X_{1a}-X_{1b}}{10}\right)^2 + \left(\frac{X_{2a}-X_{2b}}{20}\right)^2 + \left(\frac{X_{3a}-X_{3b}}{200}\right)^2} \quad (1)$$

Where:

- Distance is the similarity score between the new data and a historical data point.
- $X_{1a}$  is the Temperature value from the new data, and  $X_{1b}$  is the Temperature value from the historical data.
- $X_{2a}$  is the Humidity value from the new data, and  $X_{2b}$  is the Humidity value from the historical data.
- $X_{3a}$  is the  $\text{CO}_2$  value from the new data, and  $X_{3b}$  is the  $\text{CO}_2$  value from the historical data.

The divisor constants 10, 20, and 200 are normalization factors that were established empirically based on an analysis of the data ranges within the training dataset for the Temperature, Humidity, and  $\text{CO}_2$  variables, respectively. The use of these factors ensures that no single variable dominates the distance calculation, thereby making the prediction results more equitable and accurate.

TABLE I  
LIFE CYCLE OF THE BLACK SOLDIER FLY FOR WASTE BIODEGRADATION

Variable	Range	Category
Temperature (°C)	25 – 30	Good
	31 – 35	Moderate
	> 36	Poor
Humidity (RH)	0 – 60	Not Good
	60 – 80	Good
	90 – 100	Poor
CO <sub>2</sub> (ppm)	< 400	Good
	400 - 700	Moderate
	> 700	Poor
Light Intensity (lux)	0 - 100	Dark
	> 200	Bright

TABLE II  
TRAINING DATA

No	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	Y
1	27.8	80.1	521	7.3
2	28.7	78.2	573	7.2
3	28.0	78.0	523	7.0
4	29.4	70.3	581	6.4
5	29.8	68.5	605	6.3
6	30.1	67.8	617	6.2
7	30.8	80.0	639	6.0
8	31.7	77.4	683	5.6
9	32.6	77.3	671	5.2
10	33.1	75.0	685	5.0
11	33.8	73.4	698	4.5
12	34.5	71.2	725	4.0
13	34.8	34.8	740	3.9

TABLE III  
DATA TESTING

Temp (°C)	Hum (RH)	CO <sub>2</sub> (ppm)	pH
31.5	75.0	660	?

Based on the experimental data, environmental parameters demonstrate a significant impact on the condition of the waste biodegradation media managed by the Black Soldier Fly (BSF). The success of the BSF life cycle heavily relies on the optimization of several key external factors, including temperature, relative humidity (RH), carbon dioxide (CO<sub>2</sub>) levels, and light intensity, as categorized in Table I. Table I establishes the baseline criteria, showing that the optimal conditions ("Good") for BSF growth occur within a temperature range of 25–30°C and a relative humidity (RH) of 60–80%. Conversely, an increase in CO<sub>2</sub> concentration above 700 ppm and extreme temperatures exceeding 36°C are classified as "Poor" conditions, which can hinder larval metabolism and decomposition efficiency.

The dynamic relationship between these environmental parameters and the chemical characteristics of the waste media (represented by the pH level) was further observed through the reference data in Table II. As shown in Table 2 (Training Data), there is a consistent negative correlation between rising temperatures, accumulating CO<sub>2</sub> and the media's pH value. When environmental conditions shift from the ideal range

toward higher stress levels (temperature rising from 27.8°C to 34.8°C and CO<sub>2</sub> surging from 521 ppm to 740 ppm), the media undergoes a drastic drop in pH, moving from a near-neutral state (7.3) to highly acidic (3.9). This downward pH trend indicates intense anaerobic degradation or the accumulation of volatile fatty acids by microbial and larval activity as ambient temperatures increase.

To validate this parameter interaction pattern, a validation test was conducted using Table 3 (Data Testing) under specific environmental conditions: a temperature of 31.5°C, humidity of 75.0%, and a CO<sub>2</sub> level of 660 ppm. Through a comparative analysis of the data patterns in Table 2, the environmental conditions in Table 3 sit in a transitional phase between data points 7 and 8 (falling into the "Moderate" temperature and CO<sub>2</sub> categories). Using a linear interpolation approach, the missing pH value for the testing data is predicted to be 5.7. This result demonstrates that environmental monitoring systems can be effectively utilized to predict the acidity (pH) of BSF biodegradation media, allowing for early intervention before the media becomes too acidic and disrupts the BSF life cycle. Detailed Calculation for the Second Row (Training Data #8):

- $\left(\frac{31.5-31.7}{10}\right)^2 = (-0.02)^2 = 0.0004$
- $\left(\frac{75.0-77.4}{20}\right)^2 = (-0.12)^2 = 0.0144$
- $\left(\frac{660-683}{200}\right)^2 = (-0.115)^2 = 0.0132$
- Total Squared Distance = 0.0004 + 0.0144 + 0.0132 = 0.0280
- Final Distance =  $\sqrt{0.0280} \approx 0.167$
- The determined pH prediction is 5.6

Based on the calculations that have been performed, it was found that the closest distance corresponds to training data #8, which has a pH of 5.6.

C. System Architecture and Materials

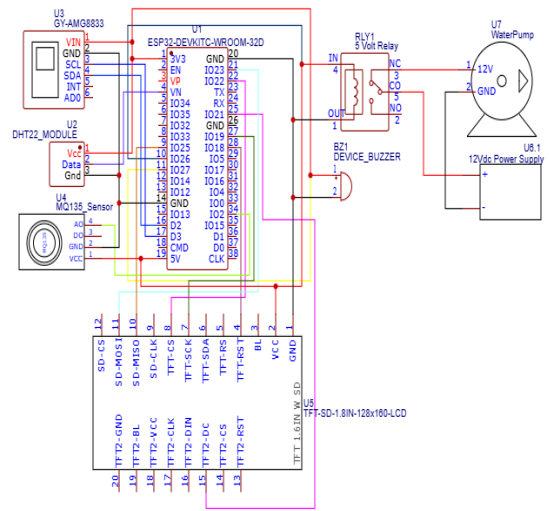


Figure 2. Series of larval growth media tools

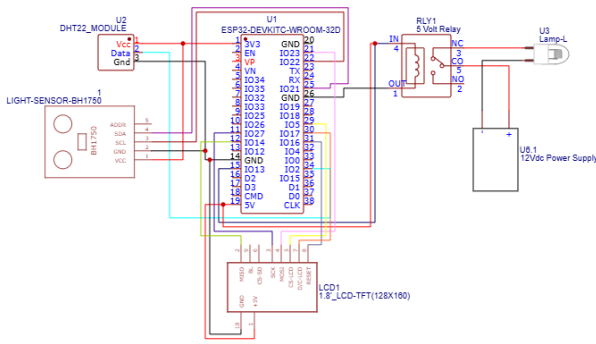


Figure 3. Series of Fly Growth Media Tools

Fig. 2 illustrates the electronic schematic diagram of the monitoring and control system designed specifically for the BSF larval growth media. The architecture is centered around an ESP32-DevKitC-WROOM-32D microcontroller as the main processing unit, which integrates four environmental sensors to track critical parameters. A GY-AMG8833 infrared array sensor monitors thermal distribution, a DHT22 module tracks ambient temperature and relative humidity, and an MQ135 sensor detects gas concentration and CO<sub>2</sub> levels. For real-time data visualization, the microcontroller is paired with a TFT 1.8-inch 128x160 LCD module via SPI communication. The actuation and alert system consist of a 5 Volt Relay that switches a 12V Water Pump powered by an external 12Vdc Power Supply to regulate moisture, alongside a device buzzer (BZ1) to provide audible alarms when environmental thresholds are breached.

Fig. 3 presents the schematic layout designed for managing the adult BSF (fly) growth media, with a specific focus on regulating light intensity and climate to stimulate mating behaviors. This system utilizes the same ESP32-DevKitC-WROOM-32D microcontroller core and a 1.8" LCD-TFT display for continuous status monitoring. The inputs are streamlined to focus on two major environmental variables: ambient climate via a DHT22 sensor and light intensity via a BH1750 digital light sensor connected through IC lines. The control loop is executed via an output pin connected to a 5 Volt Relay, which automates the activation of a 12V Lamp. Powered by an external 12Vdc Power Supply, this lamp provides artificial light supplementation whenever the ambient lux falls below the required threshold for optimal adult fly activity.

- **ESP32**  
For Internet of Things (IoT) applications, the ESP32 is a low-power, high-performance microcontroller equipped with Wi-Fi and Bluetooth capabilities. This device is capable of processing data in real-time and managing multiple devices simultaneously. The ESP32 is widely used in environmental monitoring systems and smart homes due to its dual-core architecture and integrated wireless connectivity.
- **DHT22**

There are two types of DHT sensors: the DHT22 and the DHT11. In this study, the DHT22 was chosen for its superior specifications, including a wider humidity reading range of 0-100% with an accuracy of  $\pm 2-5\%$ , and a temperature reading range of -40 to 80°C with an accuracy of  $\pm 0.5^\circ\text{C}$ . A notable drawback of the DHT22, however, is its slower data sampling rate, requiring a minimum of 2 seconds between readings.

- **AMG8833**  
This is a sophisticated thermal camera, yet it is compact and simple enough for integration. This component measures temperatures ranging from 0°C to 80°C (32°F to 176°F) with an accuracy of  $\pm 2.5^\circ\text{C}$  ( $\pm 4.5^\circ\text{F}$ ). The AMG8833 can detect a human from a distance of up to 7 meters (23 feet). It has a maximum frame rate of 10Hz.
- **MQ-135**  
The MQ-135 is commonly used to detect CO<sub>2</sub> as well as other hazardous gases such as benzene, NO<sub>x</sub>, and ammonia (NH<sub>3</sub>). Its readings are crucial for determining biogas purity and the potential presence of gaseous pollutants.
- **BH-1750**  
The BH1750 is a digital sensor used to measure light intensity in the unit of lux. This sensor is designed to mimic the spectral response of the human eye, making its measurements highly relevant for applications related to human visual perception.
- **LCD(2.4TFT)**  
This LCD serves as a display for showing measurement results, images, text, and graphics from the Arduino project. It can also function as the user interface for the project. In addition to its display and interface capabilities, the module includes a memory card slot that can be used to store images in BMP format, which can then be displayed as the LCD's background.
- **Buzzer**  
A buzzer is an electronic component that can produce sound vibrations in the form of sound waves. An electronic buzzer generates these sound vibrations when a specific level of electrical voltage is applied, in accordance with the specifications of the buzzer itself.
- **Waterpump**  
A water pump is utilized to control the temperature and humidity conditions within the enclosure. In this research, its function is to pump water through a nozzle, releasing it in the form of a fine mist.
- **Relay**  
A relay enables a low-voltage device to control a high-voltage system, such as a water heater or a pump. In this research, the relay ensures electrical isolation and safety during the switching process (turning on/off) of high-power components.
- **MiFi**  
MiFi is an abbreviation for "Mobile Wi-Fi," a term that refers to a portable wireless router that acts as a mobile Wi-Fi hotspot. This device obtains internet access from a cellular network (such as 4G LTE or 5G) via a SIM

card and then shares this connection with other nearby devices over a local Wi-Fi network.

*D. Flowchart System*

Fig. 4 explain about this IoT monitoring and control system is designed to comprehensively manage the growth medium for BSF larvae. The system utilizes an ESP32 microcontroller connected to a series of sensors, including the DHT22 (temperature/humidity) and the MQ-135 (CO<sub>2</sub> level), for real-time environmental data acquisition.

The system's logic is executed through two mechanisms. First, a rule-based control is run locally on the ESP32. The

device compares temperature and humidity data against predefined thresholds ('Good', 'Moderate', 'Poor'). If a 'Poor' condition is detected, an actuator such as a water pump is automatically activated for corrective action. Second, all raw sensor data is sent to a database for server-side analysis. A Decision Tree model then processes this data to predict complex parameters, such as the pH value of the medium. The final results from the sensors and the model's predictions are displayed comprehensively on a web interface, allowing users to perform in-depth remote monitoring and analysis.

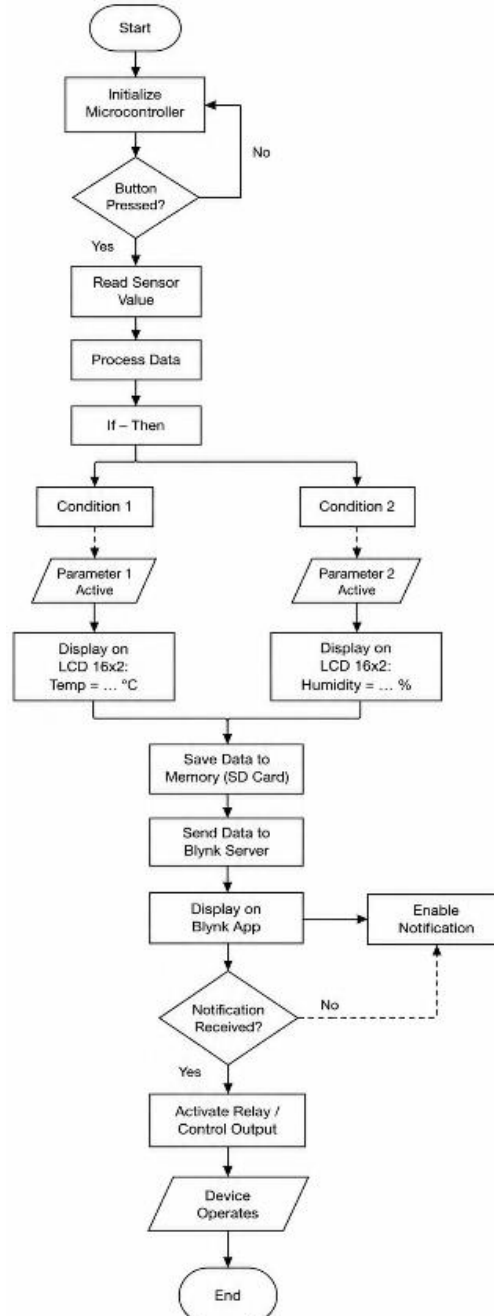


Figure 2. Flowchart of the larval growth media working system

Fig. 5 explain about this IoT control system is specifically designed to manage the enclosure environment for adult BSF flies. By utilizing an ESP32 microcontroller, a temperature sensor (DHT22), and a light sensor (BH-1750), the system executes a local, rule-based control logic to maintain optimal conditions.

Its primary mechanism is to automatically activate a light only when two conditions are met simultaneously: the ambient

temperature drops below the productive threshold (24.4°C), and the light intensity falls below the level required for mating activity (110  $\mu\text{mol m}^{-2}\text{s}^{-1}$ ). This corrective action aims to provide the necessary heating and illumination to support the reproductive process of the adult flies. All measurement data is also sent to a database and displayed on a web interface for remote historical monitoring purposes.

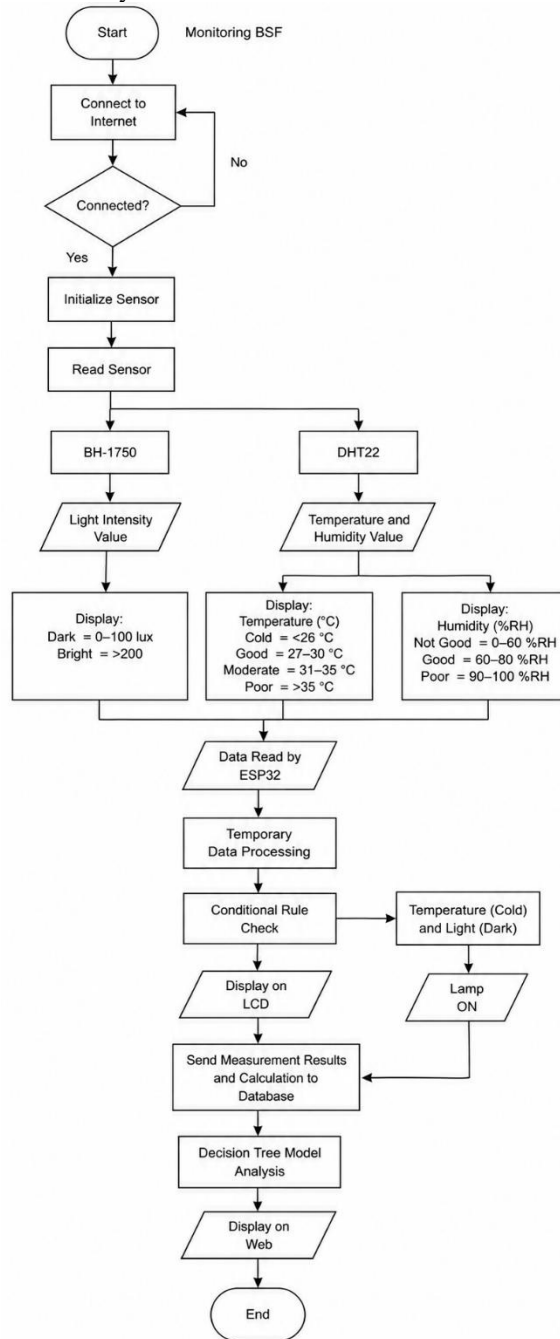


Figure 3. Flowchart of the fly monitoring work system

### III. RESULTS AND DISCUSSION

#### A. Discussion of Accuracy Test Data for Temperature and Humidity Measurement

Based on the results of the accuracy test for temperature and humidity measurement, it can be concluded that the DHT22 sensor provides highly accurate results. Fig. 6 is a further analysis of the data presented.

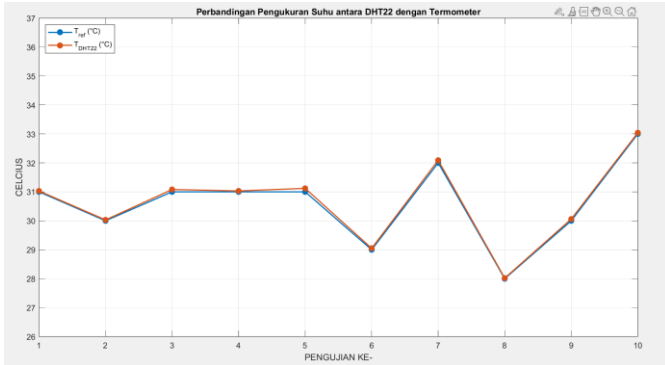


Figure 6. Temperature measurement comparison chart

The graph presented in Fig. 6 illustrates the comparison between temperature measurements obtained from the DHT22 sensor and those recorded using a reference thermometer during the validation process. The comparison was conducted to evaluate the measurement performance of the DHT22 sensor and determine its suitability for implementation in the proposed automated BSF cultivation system.

Based on the plotted results, the temperature readings produced by the DHT22 sensor demonstrate a high level of consistency with the reference thermometer measurements. The sensor successfully follows the same fluctuation patterns and temperature trends observed in the reference instrument throughout all testing periods. The close agreement between both measurement sources indicates that the DHT22 sensor is capable of accurately capturing environmental temperature variations under real operating conditions.

Furthermore, the recorded data points from the DHT22 sensor show only a minimal deviation from the reference values, indicating a relatively small measurement offset. This small difference suggests that the sensor provides stable readings with a low measurement error, which is essential for maintaining reliable environmental monitoring. The ability to detect temperature changes accurately allows the control system to respond appropriately when environmental conditions deviate from the desired range.

The high convergence between the DHT22 sensor measurements and the reference thermometer confirms the reliability of the sensor as a temperature monitoring component. This accuracy is particularly important in BSF cultivation, where temperature stability plays a significant role in supporting larval development and maintaining optimal growth conditions. Therefore, the validation results demonstrate that the DHT22 sensor can be effectively integrated into the IoT-based monitoring and control system for real-time thermal management.

Overall, the sensor evaluation confirms that the developed monitoring system is supported by reliable measurement hardware, providing a strong foundation for subsequent automated control processes and data-driven decision-making within the BSF cultivation environment.

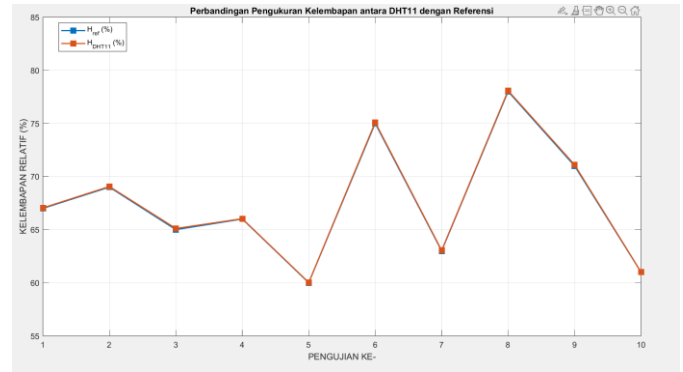


Figure 7. Humidity measurement comparison chart

The graph presented in Fig. 7 illustrates the comparison between humidity measurements obtained from the DHT22 sensor and those measured using a hygrometer as a reference instrument. This evaluation was performed to assess the reliability and accuracy of the DHT22 sensor in monitoring humidity conditions within the BSF cultivation environment. The measurement results used for generating the graph were obtained from the experimental data presented in Table 6.

Based on the plotted results, the humidity readings generated by the DHT22 sensor show a similar trend and closely follow the measurement patterns recorded by the reference hygrometer. Throughout the testing process, both measurement instruments demonstrate consistent responses to changes in environmental humidity conditions. This close correlation indicates that the DHT22 sensor is capable of accurately capturing humidity variations and providing reliable real-time monitoring data.

Although several measurement points show slight differences between the DHT22 sensor and the hygrometer readings, these variations remain within an acceptable range and do not significantly affect the overall measurement trend. The observed differences may be attributed to the sensitivity characteristics, response time, and measurement tolerance of each instrument. Nevertheless, the small deviation indicates that the DHT22 sensor provides stable and consistent humidity measurements suitable for integration into the automated cultivation system.

Accurate humidity monitoring is an essential aspect of BSF cultivation because humidity conditions directly influence larval development, biological activity, and overall cultivation performance. The ability of the DHT22 sensor to provide reliable humidity data enables the control system to detect environmental changes and perform appropriate regulation when necessary. Therefore, the validation results confirm that the DHT22 sensor is a suitable component for supporting real-time environmental monitoring and automated control within the proposed IoT-based BSF cultivation system.

Overall, the temperature and humidity validation results presented in Fig. 6 and Fig. 7 demonstrate that the implemented sensing system provides accurate and consistent environmental measurements. These reliable sensor outputs serve as the foundation for maintaining optimal cultivation conditions and improving the effectiveness of the automated monitoring and control framework.

TABLE IV

TEMPERATURE AND HUMIDITY MEASUREMENT ACCURACY TESTING						
No	T <sub>ref</sub> (°C)	T <sub>DHT2</sub> (°C)	Error <sub>T</sub> (%)	H <sub>ref</sub> (%)	H <sub>DHT1</sub> (%)	Error <sub>H</sub> (%)
1	31	31.03	0.10	67	67.05	0.07
2	30	30.03	0.10	69	69.06	0.09
3	31	31.08	0.26	65	65.11	0.17
4	31	31.03	0.10	66	66.03	0.05
5	31	31.12	0.39	60	66.03	0.05
6	29	29.05	0.17	75	75.10	0.13
7	32	32.09	0.28	63	63.05	0.08
8	28	28.02	0.07	78	78.08	0.10
9	30	30.06	0.20	71	71.11	0.15
10	33	33.04	0.12	61	61.02	0.03
Mean Error T = 0.18%			Mean Error H = 0.09%			

Table IV presents the accuracy testing results of temperature and humidity measurements obtained from the DHT22 sensor compared with reference measurement instruments. This evaluation was conducted to determine the performance and reliability of the DHT22 sensor as an environmental monitoring component in the proposed system. The comparison was performed by analyzing the difference between the reference values and the sensor output, which is represented as measurement error.

For temperature measurement, the reference temperature values (T<sub>ref</sub>) were compared with the readings obtained from the DHT22 sensor (T<sub>DHT22</sub>). The results show that the sensor readings closely match the reference thermometer measurements, with temperature errors ranging from 0.07% to 0.39%. The average temperature measurement error obtained from all testing samples is 0.18%, indicating that the DHT22 sensor provides highly accurate temperature measurements with only a minimal deviation from the reference instrument.

Similarly, the humidity measurement performance was evaluated by comparing the reference humidity values (H<sub>ref</sub>) with the humidity readings generated by the DHT22 sensor (H<sub>DHT22</sub>). The results demonstrate that the sensor is capable of accurately measuring humidity levels, with the recorded error values ranging from 0.03% to 0.17%. The average humidity measurement error is calculated as 0.09%, which indicates a high level of consistency between the DHT22 sensor and the reference hygrometer.

The low error values obtained from both temperature and humidity measurements confirm that the DHT22 sensor has reliable measurement accuracy and can effectively capture environmental changes. The small difference between sensor readings and reference values may occur due to sensor tolerance, response time, or differences in measurement conditions between instruments. However, these deviations

remain very small and do not significantly affect the monitoring performance.

These results validate that the DHT22 sensor is suitable for integration into the IoT-based BSF cultivation monitoring system. Accurate temperature and humidity measurements are essential because these parameters directly influence the stability of the cultivation environment and affect BSF larval growth performance. Therefore, the accuracy testing confirms that the developed system is supported by reliable sensing components for real-time environmental monitoring and automated control.

**B. Discussion of Accuracy Test Data for CO<sub>2</sub> Measurement**

Based on the results of the CO<sub>2</sub> measurement accuracy test, it can be concluded that the MQ-135 sensor provides highly accurate results in measuring CO<sub>2</sub>. The following is a further analysis of the data in Fig. 8.

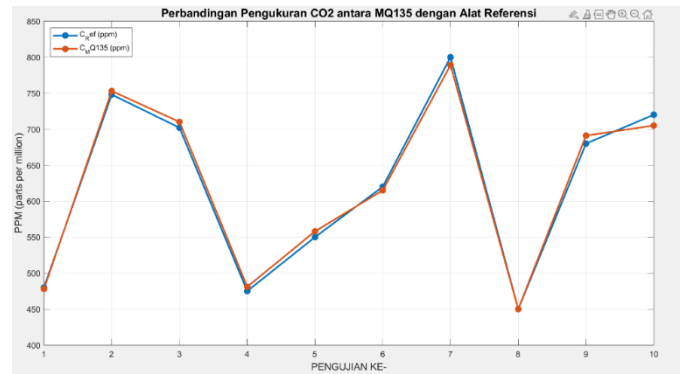


Figure 8. CO<sub>2</sub> measurement comparison chart

The graph in the Fig. 8 shows the relationship between the CO<sub>2</sub> level measurements by the MQ135 sensor and the values measured by a reference tool. From the graph, it is clear that both lines (sensor data and reference data) have very similar fluctuation patterns and are close to each other at every test point. This indicates that the MQ135 sensor is capable of responding well to changes in CO<sub>2</sub> concentration and has a low margin of error. The CO<sub>2</sub> graph is based on the measurement results in the Table V.

TABLE V  
ACCURACY TESTING OF CO<sub>2</sub> MEASUREMENT

No.	C <sub>Ref</sub> (ppm)	C <sub>MQ135</sub> (ppm)	Error (%)
1	480	478	0.42
2	748	753	0.67
3	702	710	1.14
4	475	481	1.26
5	550	558	1.45
6	620	621	0.16
7	800	799	0.13
8	450	451	0.22
9	680	679	0.15
10	705	705	0.00
Mean Error C = 0.56%			

**C. Discussion of Prediction Model Accuracy Test Data**

The main function of the Decision Tree method in this system is to determine the environmental acidity classification of the larva's growth medium, by grouping it into categories

such as 'optimal', 'moderate', or 'poor'. As input data to perform this classification, the model does not use pH values directly, but rather environmental parameters such as temperature, humidity, and CO<sub>2</sub> gas. The success of this model, which was validated with a high accuracy of 94.84%, is strong evidence that there is indeed a consistent and learnable relationship between the combination of these parameters and the actual acidity conditions.

The theoretical foundation that supports the feasibility of this prediction model stems from the working principle of a pH sensor. This principle is electrochemical transduction, which functionally correlates the activity of hydrogen ions (H<sup>+</sup>) with the electrical potential difference generated at the electrode terminals. This correlation characteristic, especially its dependence on the temperature variable, is mathematically modeled by the Nernst Equation.

Table VI outlines the predictive performance and validation results of the Decision Tree model across 24 distinct testing datasets. In this machine learning framework, three environmental parameters serve as the independent input variables: ambient temperature, relative humidity, and carbon dioxide concentration. These inputs are utilized by the algorithm to estimate the dependent variable, which is the actual acidity level of the BSF larval growth media. By comparing the experimentally recorded actual values against the model's predictions, the Absolute Percentage Error (APE) for each individual trial was computed to evaluate the model's reliability under varying microhabitat conditions.

An in-depth analysis of the data points reveals that the Decision Tree model demonstrates high precision within the optimal and moderate growth ranges. For instance, in trials 2, 3, and 4—where temperatures ranged between 30.1 and 31.7—the model achieved an error rate of 0.00, yielding perfect alignment between the actual and predicted values. Conversely, marginally higher error rates are observed at the extreme boundaries of the experimental spectrum. The maximum deviations occurred in trial = 12.50% and trial 24 = 12.82%, where the system was subjected to high thermal stress >34 and peak CO<sub>2</sub> accumulation >720. This slight inflation in error suggests that extreme environmental thresholds introduce complex, non-linear biochemical dynamics within the organic waste media that slightly challenge the linear split boundaries of a conventional decision tree structure.

Despite these localized marginal deviations at extreme values, the overall performance of the algorithm remains exceptionally robust, yielding an overall Mean Error Rate of 5.16%. This corresponds to a remarkable predictive accuracy of 94.84%. Such a high degree of convergence mathematically validates the core hypothesis of this research: complex and hard-to-measure biological substrates, such as medium pH, can be successfully predicted using readily accessible environmental proxy variables X<sub>1</sub>, X<sub>2</sub>, and X<sub>3</sub>. Implementing this data-driven Decision Tree approach eliminates the necessity for continuous, direct physical PH probe submersion, which is notoriously prone to rapid sensor fouling and degradation in aggressive organic decomposition environments.

TABLE VI  
DECISION TREE PREDICTION ACCURACY TESTING

No.	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	(Y)	pH Prediction	(%)
1	27.2	81.5	505	7.5	7.4	1.33
2	30.1	67.8	617	6.2	6.2	0.00
3	30.4	77.7	633	6.1	6.1	0.00
4	31.7	77.4	683	6.0	6.0	0.00
5	28.0	78.0	523	7.0	6.8	2.86
6	30.6	79.0	672	5.9	5.7	3.39
7	32.6	77.3	671	5.2	5.0	3.85
8	30.8	80.0	639	5.6	5.3	5.36
9	28.7	78.2	573	7.2	6.9	4.17
10	29.4	70.3	581	6.4	6.1	4.69
11	34.5	71.2	725	4.0	4.5	12.50
12	34.1	72.0	710	4.2	4.6	9.52
13	33.8	73.4	698	4.5	4.8	6.67
14	33.5	74.1	691	4.8	5.1	6.25
15	33.1	75.0	685	5.0	5.4	6.00
16	32.8	76.5	678	5.1	5.4	5.88
17	31.2	78.8	655	5.8	5.5	5.17
18	29.8	68.5	605	6.3	6.0	4.76
19	29.0	75.5	568	6.8	6.5	4.41
20	28.2	79.4	540	6.9	6.6	4.35
21	27.8	80.1	521	7.3	7.0	4.11
22	32.0	79.2	695	5.5	5.2	5.45
23	28.4	76.9	555	7.1	6.8	4.23
24	34.8	70.8	740	3.9	4.4	12.82
Mean Error Rate = 5.16%						

This research addresses the fundamental challenge of uncertainty in Black Soldier Fly (BSF) cultivation, where environmental conditions significantly influence larval growth and survival. Conventional cultivation practices often depend on manual observation and farmer intuition, causing important parameters such as medium pH and humidity to remain undetected until they have already affected the cultivation process. This limitation highlights the need for a more systematic approach that can provide continuous monitoring and early detection of environmental changes.

To overcome these challenges, the proposed system introduces a paradigm shift from reactive management toward a proactive, data-driven cultivation strategy. By utilizing real-time environmental monitoring and intelligent data analysis, the system aims to improve cultivation consistency, optimize growth conditions, and minimize potential losses caused by unfavorable environmental changes.

The core innovation of this research lies in the implementation of a hybrid architecture that combines local control and centralized intelligence. At the local level, ESP32 microcontrollers act as an autonomous control unit by monitoring and managing environmental parameters, particularly temperature and humidity, to maintain stable cultivation conditions while reducing the need for manual intervention.

Meanwhile, the central server functions as an intelligent processing unit that analyzes collected sensor data using a Decision Tree model. Through this approach, the system is capable of estimating complex parameters, such as cultivation medium pH, based on measurable proxy parameters such as CO<sub>2</sub> emissions. This predictive capability enables the system to identify potential problems earlier, allowing timely corrective actions before conditions become critical.

The integration of immediate local control and predictive analytical capabilities establishes an effective early warning system for BSF cultivation. The effectiveness of this proactive approach is further demonstrated through the cultivation cycle results, which are presented and visually supported in the corresponding figures.



Figure 9. BSF egg clutches as baseline material

Fig. 9 presents a sample of Black Soldier Fly (BSF) egg clutches before being introduced into the proposed automated cultivation system. These egg clutches represent the initial biological material used as the baseline condition for the cultivation process. At this stage, the eggs serve as the starting point for evaluating the performance of the monitoring and control system throughout the BSF growth cycle.

The quality and condition of the egg clutches are important factors that influence the subsequent larval development process. Therefore, documenting the initial state of the BSF eggs provides a reference point for observing changes in growth, environmental adaptation, and system effectiveness during the cultivation period. The baseline data obtained from this initial phase is essential for comparing cultivation outcomes after the implementation of automated monitoring, environmental regulation, and predictive analysis mechanisms.

By establishing the BSF egg clutches as the initial reference material, the research ensures that the cultivation process can be systematically evaluated from the beginning until the later growth stages. This approach supports the assessment of how the proposed system maintains optimal environmental conditions and contributes to improving the consistency and reliability of BSF cultivation results.

Figure 10 illustrates the outcome of the incubation process after the BSF egg clutches were placed inside the controlled cultivation system. The figure shows the successful mass hatching process, characterized by the emergence of a high density of newly hatched neonate larvae. This observation indicates that the environmental conditions maintained by the automated system were suitable to support the embryonic development process from the egg stage to the early larval stage.

The successful emergence of neonate larvae demonstrates the effectiveness of the proposed environmental monitoring and control mechanism in maintaining stable cultivation conditions. During the incubation period, critical parameters

such as temperature and humidity were continuously monitored and regulated to ensure that the eggs remained within the optimal range required for successful hatching. The ability of the system to maintain these parameters consistently reduced the risk of environmental fluctuations that could negatively affect embryo viability and hatching success.

Furthermore, the high density of newly emerged larvae provides an initial indication of the system's capability to improve cultivation reliability compared with conventional approaches that rely primarily on manual observation. The automated control strategy enables a more stable and predictable incubation environment, allowing the biological process to proceed under favorable conditions with minimal human intervention.

This successful mass hatching event serves as an important validation point for the developed system, confirming that the integration of real-time monitoring, automated environmental regulation, and data-driven management can effectively support the early stage of BSF cultivation. The results obtained from this phase provide a strong foundation for evaluating the subsequent larval growth performance and overall efficiency of the proposed automated cultivation framework.



Figure 10. Successful mass hatching and emergence of neonate larvae in the controlled system



Figure 11. Size uniformity of BSF larval at the harvest stage as an indicator of system success

Fig. 11 presents the condition of the BSF larvae at the harvest stage after completing the cultivation process within the automated controlled environment. The figure highlights the physical appearance and size distribution of the harvested larvae, where a high degree of size uniformity can be observed

among the larval population. This uniform growth pattern serves as an important indicator of the stability and effectiveness of the developed cultivation system in maintaining favorable conditions throughout the growth period.

The uniformity in larval size reflects the consistency of environmental conditions provided by the system, particularly in maintaining essential parameters that influence larval development. Continuous monitoring and automatic regulation of cultivation parameters help minimize fluctuations that may cause differences in growth rates among individual larvae. As a result, the system is capable of reducing the occurrence of underdeveloped larvae and promoting more synchronized growth across the population.

In conventional BSF cultivation methods, variations in environmental conditions often lead to non-uniform growth, where some larvae may experience slower development due to suboptimal conditions. The proposed system addresses this limitation by providing a controlled environment supported by real-time monitoring and automated decision-making mechanisms. This approach improves cultivation reliability by ensuring that the larvae receive consistent conditions throughout their development cycle.

From a production perspective, larval size uniformity is a critical factor because it directly affects harvest efficiency, biomass quality, and product value. A more homogeneous larval population enables more predictable harvesting schedules and simplifies post-harvest processing. Therefore, the results shown in Figure 11 demonstrate that the developed system not only supports biological growth but also contributes to improving the scalability and commercial feasibility of BSF cultivation.

Overall, this research provides more than the implementation of an IoT-based monitoring device. The proposed framework represents a transformation of BSF cultivation from a traditional practice that relies heavily on experience and intuition into a measurable, controlled, and data-driven agricultural process. Through precise environmental management and remote supervision via a web-based interface, the system establishes a foundation for more efficient, consistent, and sustainable BSF farming toward future industrial-scale implementation.

#### IV. CONCLUSION

The predictive model is integrated with an Internet of Things (IoT)-based cultivation platform consisting of ESP32 microcontrollers, environmental sensors, and automated actuators. This integration enables the system to perform real-time monitoring and automatic regulation of important cultivation parameters, particularly temperature and medium conditions. The actuator mechanisms allow the system to maintain environmental stability by responding to detected changes without requiring continuous human intervention. The high prediction accuracy achieved by the Decision Tree Regression model demonstrates the reliability of the proposed approach in representing the relationship between measurable environmental parameters and the pH condition of the BSF

larvae medium. This capability is particularly beneficial because medium pH is one of the critical factors influencing microbial activity, nutrient availability, and larval growth performance. Therefore, early detection and prediction of pH variations allow the system to maintain a more suitable environment throughout the cultivation cycle. Furthermore, the implementation of automated monitoring and control mechanisms has been shown to improve cultivation consistency and biomass production performance compared with cultivation methods without automatic regulation. By maintaining stable growth conditions, the system minimizes environmental fluctuations that may negatively affect larval development and reduces variations in cultivation outcomes. Overall, the integration of predictive analytics and IoT-based automation provides a comprehensive approach for advancing BSF cultivation management. The developed system demonstrates the potential to transform traditional cultivation practices into a more precise, efficient, and data-driven process, supporting future scalability and sustainable implementation in industrial BSF farming.

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