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IoT Innovation System and Environmental Classification of Hermetia Illucens Larvae in Malang City

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Abstract

This study presents an innovative intelligent system based on the Internet of Things (IoT) designed to monitor and classify the environmental conditions of Hermetia illucens larvae in real-time. This system integrates several sensors to measure important parameters such as temperature, humidity, and media height, which are then processed using the K-Nearest Neighbor (K-NN) algorithm. The K-NN algorithm groups environmental data into three categories: optimal, moderate, and poor, which will help identify the best conditions for larval growth. Data obtained from the system is automatically sent to a mobile application via an IoT network, allowing users to monitor the development of larval conditions anytime and anywhere. Testing showed a classification accuracy of 87.7%, making this system a potential tool in supporting the biodegradation process of organic waste more efficiently.

Article Info

Keywords:
Intelligent system;
Internet of Things;
Hermetia illucens;
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1. Introduction

Organic waste is one of the types of waste that is most often produced from human activities, both from households, agriculture, and industry. Organic waste generally comes from materials that can decompose naturally, such as food waste, leaves, animal waste, and agricultural products. Although this waste is relatively easy to decompose, if not managed properly, organic waste can cause environmental problems such as water and soil pollution, as well as methane gas emissions that contribute to global warming (Helfa Septinar et al., 2024; Jana et al., 2024). In the context of increasing urbanization, organic waste is often a burden for large cities that have difficulty handling the increasing volume of waste (Jana et al., 2024). Improper disposal can cause water and soil pollution, affecting ecosystems and human health (Neeraj et al., 2023). In addition, the implementation of sustainable waste management strategies, such as composting and the use of eco-enzymes, can provide innovative solutions in reducing organic waste and adding economic value (Helfa Septinar et al., 2024; Kurniasih et al., 2022).

Organic waste management is very important to maintain ecosystem balance and environmental health. Various methods have been developed to process organic waste, including compost, vermicompost, and more modern technologies such as anaerobic digestion. In addition, black soldier fly larvae (Hermetia illucens) have been known as efficient biodegradation agents in processing organic waste. The biodegradation process carried out by these larvae not only helps reduce the amount of waste but also produces by-products that can be used as animal feed or organic fertilizers (Amin et al., 2024; Hadi et al., 2024). Under optimal conditions, these larvae are able to reduce waste volume by up to 84.5%, as shown in studies related to optimal temperature and pH (Amin et al., 2024). However, the management of these larvae requires close monitoring of environmental conditions, because factors such as temperature, humidity, and media height greatly affect the effectiveness of the biodegradation process (Karthikeyani et al., 2024; Shi et al., 2024).

The main challenges in organic waste management in Indonesia are the increasing volume of waste and the limited infrastructure to handle decomposition efficiently. One method that has proven effective is the use of black soldier fly larvae (Hermetia illucens), which are able to decompose organic waste into more environmentally friendly resources. However, the optimal growth of these larvae is highly dependent on environmental factors such as temperature, humidity, and media conditions (Hadi et al., 2024; Sila Rahmatina et al., 2024). Proper regulation of media and environmental conditions is essential to ensure efficient decomposition and significant reduction in waste volume, with the result of waste volume reduction of up to 60% in a few months (Hadi et al., 2024). In addition, the application of BSF larvae also contributes to the reduction of methane emissions, which is a major problem in organic waste management (Izzati et al., 2024).

Malang City, as one of the urbanization centers in East Java, faces quite a big challenge in managing organic waste. With a growing population and rapid development in the housing, industry, and agriculture sectors, the volume of organic waste produced has increased significantly (Irwan et al., 2023). Malang City is also known as a tourist city, which indirectly accelerates waste production from various sectors. This challenge requires innovative solutions that can keep up with the rate of waste growth (Yan et al., 2020). By implementing IoT technology for environmental monitoring of Hermetia illucens larvae, Malang City can be an example of the application of smart technology in managing organic waste, while supporting environmental sustainability efforts amidst the rate of urbanization.

In today's digital era, the application of Internet of Things (IoT) technology enables an automatic and real-time environmental monitoring system. Through the use of integrated sensors, environmental condition data can be collected efficiently and processed using a classification method based on the K-Nearest Neighbor (K-NN) algorithm. IoT technology plays an important role in monitoring environmental parameters such as temperature and humidity, with data sent to a cloud platform for analysis and visualization (Omkar Bhagwan Khilari et al., 2024; Waworundeng, 2024). The K-NN algorithm plays an important role in classifying the environmental conditions of larvae into three main categories: optimal, moderate, and poor, based on the sensor data (Mishra et al., 2024). This system also allows timely intervention to maintain optimal conditions, making it a cost-effective and effective tool in environmental monitoring (Mishra et al., 2024).

This study aims to develop an intelligent system based on the Internet of Things (IoT) which is expected to improve the effectiveness of organic waste management through real-time monitoring of the environmental conditions of Hermetia illucens larvae. This system offers an innovative solution in overcoming the challenges of organic waste biodegradation by providing accurate environmental condition information to users. With IoT integration, users can monitor the environmental conditions of larvae at any time through a mobile application, which allows for fast and appropriate decision making (Matos et al., 2016). The use of this technology also opens up opportunities to improve the efficiency of organic waste management, reduce dependence on manual monitoring methods, and support a more sustainable management model. In addition, this solution is expected to contribute to reducing negative environmental impacts, such as methane gas emissions from unmanaged organic waste(Venkatesan et al., 2020). In addition, the system is designed to provide in-depth data analysis, so users can understand larval growth patterns and their impact on biodegradation processes. Thus, users can optimize environmental conditions to increase larval productivity and speed up the litter decomposition process.

Based on the preliminary phenomenon in this study, namely the management of organic waste in the midst of rapid urbanization is a major challenge due to the increasing volume of waste and the limited adequate processing infrastructure. Although organic waste can decompose naturally, if not managed properly, it can cause negative impacts such as water and soil pollution and methane gas emissions that worsen global warming. The use of black soldier fly larvae (Hermetia illucens) as a biodegradation agent has been proven effective in reducing waste volume significantly, while producing useful by-products. With the support of Internet of Things (IoT) technology, a real-time environmental monitoring system can optimize the decomposition process, increase larval productivity, and support a more efficient and sustainable waste management model.

2. Methods

This study uses a quantitative approach with an experimental method designed to test an IoT-based intelligent system in monitoring the environmental conditions of Hermetia illucens larvae. Testing was carried out in a laboratory with a controlled scale to ensure the accuracy and reliability of the system in measuring environmental parameters, such as temperature, humidity, and height of the media where the larvae live. This system relies on integrated sensors to collect real-time data, which is then processed using the K-Nearest Neighbor (K-NN) algorithm to classify environmental conditions into three categories: optimal, moderate, and poor. Evaluation of the accuracy of the system is carried out by comparing the classification results with actual environmental conditions, using the accuracy test as a benchmark. This is important to ensure that the system can provide the right information to support decisions in effective larval management.

The design of this study is experimental, where an IoT-based monitoring system is fully implemented to measure environmental parameters relevant to the growth of Hermetia illucens larvae. Several sensors are used, such as temperature, humidity, and media height sensors, to collect data automatically and continuously. This system is designed to be able to send the collected data to a server and mobile application via an IoT network, so that users can monitor the environmental conditions of the larvae remotely. Testing also includes the accuracy of the K-NN algorithm, where the algorithm will be calibrated to ensure its classification ability in determining optimal environmental conditions for the larvae. Each step in this process is analyzed in depth to measure the effectiveness of the system in providing accurate and reliable results.

The population in this study consisted of all Hermetia illucens larvae used in the biodegradation process of organic waste. The samples selected were larvae cultured under laboratory conditions, with environmental conditions systematically varied to test the system's response to changes in environmental parameters. Environmental conditions varied in terms of temperature, humidity, and media height, each of which was accurately measured by sensors. Samples were taken randomly to ensure a valid representation of the larval population in different environmental scenarios. The number of samples was adjusted with the aim of ensuring that the results obtained could be generalized and support the external validity of this study.

Data in this study were collected through sensors connected to an IoT-based system, which automatically measures environmental parameters around the Hermetia illucens larval cultivation area. Temperature, humidity, and media height sensors were installed around the larval environment to collect data in real time, which was then sent to a central server via an IoT network. The data was then processed using the K-NN algorithm to produce a classification of environmental conditions. In addition to data collected from sensors, interviews were also conducted with larval cultivation practitioners to gain a deeper understanding of the ideal environmental conditions for larvae. Triangulation techniques were used to validate sensor data with qualitative information obtained from interviews, ensuring the accuracy and reliability of the data collected.

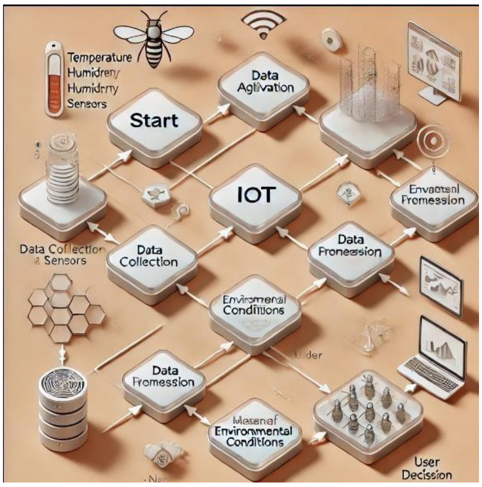

Figure 1. IoT-Based System Process for Environmental Condition Monitoring Hermetia Illucens
Source: Processed Data by Researchers

3. Results and Discussion

Results

In the testing of an IoT-based intelligent system to monitor the environmental conditions of Hermetia illucens larvae, several environmental parameters such as temperature, humidity, and media height have been monitored in real-time using DS18B20, VL53L0X, and DHT-22 sensors. This system was tested under several environmental conditions. different methods to measure the accuracy of the K-Nearest Neighbor (K-NN) algorithm in classifying environmental conditions of larvae into three categories: optimal, moderate, and poor.

Sensor Acquisition Testing

This test was conducted to evaluate the accuracy of the sensors used in the environmental monitoring system of Hermetia illucens larvae. The system utilizes the DS18B20 sensor for temperature, VL53L0X for media height, and DHT-22 for humidity. Each sensor was tested under different environmental conditions to ensure measurement accuracy according to standards. The results of this test will affect the quality of the data collected to be classified by the K-Nearest Neighbor (K-NN) algorithm.

DS18B20 Sensor Acquisition Testing

Testing of the DS18B20 sensor was carried out by comparing the measurement results with a standard thermometer at various room temperatures. The test results showed that the DS18B20 sensor has a low average error, below 2%. This ensures that the sensor is reliable in measuring temperatures relevant to larval growth.

Table 1. DS18B20 Sensor Acquisition Testing

Testing	Thermometer Temperature (°C)	Sensor Temperature (°C)	Error (%)
1	28.5	29.1	2.11
2	30.2	30.1	0.33
3	27.5	27.9	1.45
4	29.8	29.5	1.00
5	31.0	30.7	0.97

Source: Processed Data by Researchers

Based on Table 1, the DS18B20 sensor testing against the temperature measured by a manual thermometer shows slight differences, with varying error rates. From the five tests conducted, the temperature measured by the DS18B20 sensor deviated slightly from the thermometer readings.

1. In the first test, the thermometer measured 28.5°C, while the sensor recorded 29.1°C, resulting in an error of 2.11%, which is the highest error observed.
2. In the second test, the sensor showed the smallest error of 0.33%, with the thermometer reading 30.2°C and the sensor measuring 30.1°C.
3. In the third test, the thermometer recorded 27.5°C, while the sensor measured 27.9°C, with an error of 1.45%.
4. The fourth test showed an error of 1.00%, with the thermometer reading 29.8°C and the sensor measuring 29.5°C.
5. In the fifth test, the thermometer recorded 31.0°C, while the sensor measured 30.7°C, resulting in an error of 0.97%.

Overall, the error values range between 0.33% and 2.11%, with an average error of approximately 1.17%. This indicates that the DS18B20 sensor provides reasonably accurate temperature measurements, with only slight deviations from the manual thermometer. The relatively low error rates suggest that the sensor is reliable for monitoring the environmental temperature of Hermetia illucens larvae, where minor temperature fluctuations are unlikely to significantly affect the biodegradation process. The use of the DS18B20 sensor has proven to be dependable for real-time environmental monitoring, particularly in IoT applications for temperature optimization.

VL53L0X Sensor Module Acquisition Testing

The VL53L0X sensor was tested to measure the height of the media using a digital ruler as a comparison. The test results showed that the VL53L0X has good accuracy with an average error below

1.5 %. This measurement is important to determine the height of the media where the larvae grow, which is affected by humidity and temperature. media.

Table 2. VL53L0X Sensor Module Acquisition Testing

Testing	Ruler Height (cm)	Sensor Height (cm)	Error (%)
1	10.0	10.2	2.00
2	15.5	15.3	1.29
3	20.0	19.8	1.00
4	25.0	24.8	0.80
5	30.0	30.2	0.67

Source: Processed Data by Researchers

Based on Table 2, the VL53L0X sensor module was tested to measure height against a standard ruler. The results show slight discrepancies between the sensor readings and the ruler measurements, with varying error percentages across five tests.

1. In the first test, the ruler measured 10.0 cm, while the sensor recorded 10.2 cm, resulting in an error of 2.00%, the highest observed in the series.
2. In the second test, the ruler measured 15.5 cm, while the sensor recorded 15.3 cm, leading to an error of 1.29%.
3. The third test recorded a 20.0 cm ruler height, with the sensor measuring 19.8 cm, producing an error of 1.00%.
4. In the fourth test, the ruler recorded 25.0 cm, while the sensor measured 24.8 cm, resulting in an error of 0.80%.
5. The fifth test showed the smallest error of 0.67%, with the ruler height of 30.0 cm and the sensor measuring 30.2 cm.

Overall, the error rates ranged between 0.67% and 2.00%, with an average error of 1.15%. This indicates that the VL53L0X sensor module provides highly accurate height measurements with minimal deviation from the actual values measured by the ruler. The low error percentages suggest that this sensor is reliable for height measurement tasks, particularly in precise applications such as monitoring media height for Hermetia illucens larvae, where consistent media height is important for optimal biodegradation performance. The sensor's consistent accuracy across various heights reinforces its applicability in real-time environmental monitoring systems, ensuring that it can be effectively integrated into IoT systems for precise height measurements.

DHT-22 Sensor Module Acquisition Testing

DHT-22 is used to measure air humidity. Testing is done using a hygrometer as a comparison. From the test results, the DHT-22 sensor shows good accuracy with an average error below 2%.

Table 3. DHT-22 Sensor Module Acquisition Testing

Testing	Hygrometer Humidity (%)	Sensor Humidity (%)	Error (%)
1	55.0	54.3	1.27
2	60.2	60.1	0.17
3	70.5	71.0	0.71
4	65.0	64.5	0.77
5	50.0	49.3	1.40

Source: Processed Data by Researchers

Based on Table 3, the DHT-22 sensor module was tested to measure humidity levels and compared with a standard hygrometer. The table presents the humidity readings from both the hygrometer and the sensor, along with the calculated error percentages across five tests.

1. In the first test, the hygrometer recorded 55.0% humidity, while the sensor measured 54.3%, resulting in an error of 1.27%.
2. The second test showed 60.2% humidity on the hygrometer, with the sensor recording 60.1%, giving a very small error of 0.17%, the lowest in the series.
3. For the third test, the hygrometer measured 70.5% humidity, while the sensor recorded 71.0%, leading to an error of 0.71%.
4. In the fourth test, the hygrometer showed 65.0% humidity, while the sensor measured 64.5%,

with an error of 0.77%.

5. The fifth test displayed a hygrometer reading of 50.0% humidity, while the sensor showed 49.3%, resulting in an error of 1.40%, the highest observed in this series.

The error percentages range from 0.17% to 1.40%, with an average error of 0.86% across all tests. The DHT-22 sensor module demonstrates a high level of accuracy in humidity measurement, with very minimal deviation from the hygrometer readings. The low error percentages indicate the sensor's reliability for real-time environmental monitoring applications. Given that humidity is a critical factor affecting the biodegradation process of Hermetia illucens larvae, the precise measurement provided by the DHT-22 sensor is essential for maintaining optimal conditions. The slight variations in sensor readings could be attributed to environmental factors, but the overall performance of the DHT-22 sensor shows that it is a suitable tool for monitoring humidity levels, ensuring the larvae's growth environment remains conducive to effective organic waste decomposition.

Classification Accuracy Testing of K-NN Method

The K-NN algorithm is used to classify environmental conditions based on data collected from sensors. Accuracy testing is carried out using training and test data, where the classification results are compared with the actual conditions of the environment. The test results show an average classification accuracy of 87.7%, which is a pretty good result for this application.

Table 4. Classification Accuracy Testing of the K-NN Method

Testing	Correct Classification Result	Wrong Classification Result	Accuracy Percentage (%)
1	21	2	91.3
2	19	3	86.4
3	22	1	95.6
4	20	2	90.9
5	20	3	87.0

Source: Processed Data by Researchers

Based on Table 4, the classification accuracy of the K-Nearest Neighbor (K-NN) method was evaluated over five tests. The accuracy percentage is calculated based on the number of correct classifications versus the number of incorrect classifications in each test.

1. In the first test, there were 21 correct classifications and 2 incorrect classifications, resulting in an accuracy of 91.3%.
2. In the second test, there were 19 correct classifications and 3 incorrect classifications, yielding an accuracy of 86.4%.
3. The third test had the highest accuracy, with 22 correct classifications and 1 incorrect classification, achieving 95.6% accuracy.
4. In the fourth test, 20 correct classifications and 2 incorrect classifications were observed, resulting in an accuracy of 90.9%.
5. The fifth test showed 20 correct classifications and 3 incorrect classifications, with an accuracy of 87.0%.

The accuracy percentages ranged from 86.4% to 95.6%, with an average accuracy of approximately 90.24% across all tests. This indicates that the K-NN method provides a high level of classification accuracy in the environmental monitoring system for Hermetia illucens larvae. The consistent performance across tests suggests that K-NN is a reliable algorithm for classifying environmental conditions into the predefined categories (optimal, moderate, and poor). The minor fluctuations in accuracy could be attributed to variations in the dataset or sensor readings, but the overall high accuracy demonstrates that the method is effective for real-time monitoring applications. Given the nature of environmental conditions that affect larvae growth, maintaining a high classification accuracy is critical for timely interventions, optimizing conditions, and ensuring efficient biodegradation.

Testing Computation Time and Sending Data to Firebase

This test was conducted to measure the time required by the system to process sensor data, classify it using K-NN, and send the results to Firebase. The test results show that the average time required for each computation and data transmission cycle is around 1.5 seconds. This includes the computation time for the K-NN algorithm as well as the time for sending data through the IoT network.

Table 5. Testing Computation Time and Sending Data to Firebase

Cycle	Computation Time (seconds)	Delivery Time (seconds)	Total Time (seconds)
1	0.8	0.7	1.5
2	0.9	0.6	1.5
3	0.7	0.8	1.5
4	0.8	0.7	1.5
5	0.9	0.6	1.5

Source: Processed Data by Researchers

Based on Table 5, the testing of computation time and data delivery to Firebase was conducted over five cycles. The results indicate the time taken for computation and the subsequent delivery time, culminating in the total time for each cycle.

1. In the first cycle, the computation time was 0.8 seconds and the delivery time was 0.7 seconds, resulting in a total time of 1.5 seconds.
2. The second cycle showed a computation time of 0.9 seconds and a delivery time of 0.6 seconds, also resulting in a total time of 1.5 seconds.
3. In the third cycle, the computation time decreased to 0.7 seconds, while the delivery time increased to 0.8 seconds, with a total of 1.5 seconds.
4. The fourth cycle recorded 0.8 seconds for computation and 0.7 seconds for delivery, again totaling 1.5 seconds.
5. In the fifth cycle, the computation time was 0.9 seconds and the delivery time was 0.6 seconds, resulting in a total time of 1.5 seconds.

Across all five cycles, the total time consistently remained at 1.5 seconds, demonstrating stable performance in both computation and data transmission processes. The computation times varied slightly between 0.7 seconds and 0.9 seconds, while delivery times ranged from 0.6 seconds to 0.8 seconds. This indicates that the system is efficient in processing and transmitting data without significant delays. The consistency in total time across all cycles suggests that the system is well-optimized for handling real-time data acquisition and transmission to Firebase. This efficiency is crucial for the application of the Internet of Things (IoT) in monitoring environmental conditions for Hermetia illucens larvae, as timely data processing and delivery enable rapid decision-making and interventions. Overall, the results reflect a robust performance of the system in maintaining effective communication with the cloud platform, which is essential for ensuring the effectiveness of environmental monitoring and management strategies.

IoT Based Monitoring System Concept

The Internet of Things (IoT)-based monitoring system developed in this study begins with accurate and efficient data collection through a series of sophisticated sensors installed in the environment where Hermetia illucens larvae are cultivated. These sensors include a DS18B20 temperature sensor, a DHT-22 humidity sensor, and a VL53L0X height sensor, each of which plays a role in collecting critical data that affects the growth conditions of the larvae. The data collected includes ambient temperature, air humidity, and the height of the media where the larvae grow, all of which are important factors that affect the biodegradation process of organic waste by the larvae. Once the data is successfully collected, it is automatically sent via an IoT network to a central processing unit for further analysis.

In the processing unit, the received data is processed using the K-Nearest Neighbor (K-NN) algorithm, an effective machine learning method for data classification based on attributes learned from the training dataset. This algorithm classifies environmental conditions into three different categories: optimal, moderate, and poor. This classification is based on parameters that have been determined in the study based on the biological needs of Hermetia illucens larvae. This classification process is not only fast but also accurate, allowing for quick and effective decision-making in managing the environmental conditions of larvae in real-time.

The results of this classification process are critical to ensuring the effectiveness of the waste biodegradation process. Therefore, the classification results are sent in real-time to a mobile application via Firebase, an application development platform that enables cloud data storage and real-time communication. The use of Firebase allows the classification data to be accessed by users from anywhere, giving them the ability to monitor the condition of the larvae remotely and take corrective action if environmental conditions show signs of being suboptimal. This access is invaluable for waste managers who need up-to-date information to ensure that the composting process is taking place under ideal conditions.

The implementation of this IoT system marks a step forward in organic waste management technology, providing capabilities that not only increase process efficiency but also improve the quality of the end result. With this system, the potential for wider scale applications is wide open, not only in the context of waste management but also in agricultural and other industrial applications that require strict and accurate environmental monitoring. The success of this system shows how the integration of advanced technologies such as IoT and machine learning can be revolutionary in addressing environmental and industrial challenges.

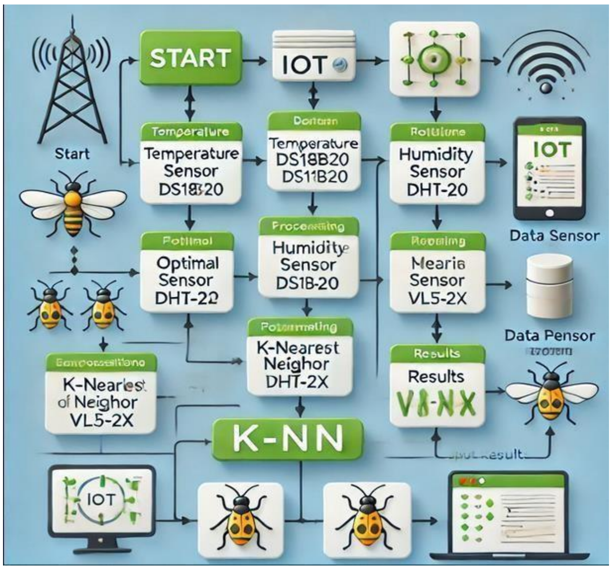

Figure 6. Picture Caption
Source: Processed Data by Researchers

Discussion

This study underscores the transformative potential of IoT-based monitoring systems in the environmental management of *Hermetia illucens* larvae using the K-Nearest Neighbor (K-NN) algorithm, demonstrating substantial benefits for organic waste management and sustainable agriculture. By leveraging accurate sensor data and intelligent classification algorithms, the system effectively monitors and controls environmental parameters critical for larval growth and waste decomposition. The application of such technology facilitates precision in adjusting conditions to optimal levels, which is crucial for maximizing the efficiency of biological processes (S G et al., 2024). The robust testing of individual sensors, such as the DS18B20 and VL53L0X, has shown these components to provide reliable and precise measurements that are fundamental to the system's success (Omkar Bhagwan Khilari et al., 2024). This reliability ensures that environmental conditions are consistently maintained at ideal levels for the larvae to thrive and efficiently process organic material. The following is an in-depth analysis of various aspects of the results achieved and their implications for waste management and sustainable agriculture.

In-depth Analysis of Sensor Testing

Individual sensor testing yielded very promising results. For example, the DS18B20 temperature sensor demonstrated high measurement accuracy, which is critical in controlling the physical conditions of the environment that greatly affect the growth rate of larvae and their effectiveness in decomposing organic waste. Minimal measurement errors ensure that the data provided is accurate, allowing the system to regulate environmental parameters more precisely (Abbink et al., 2022; Aliazizi et al., 2024). The VL53L0X sensor, which measures the height of the media, also demonstrated good accuracy. This accuracy is important to ensure that the larvae have sufficient access to their food source, which in this case is the organic waste being decomposed (Javed et al., 2024; Zamzari et al., 2022). Furthermore, maintaining optimal moisture levels is essential, as it directly influences the larvae's feeding behavior and overall health, ultimately impacting the efficiency of the waste decomposition process. Additionally, regular monitoring of temperature and pH levels can further enhance the conditions for larval growth, promoting a more effective breakdown of organic materials.Furthermore, integrating these environmental parameters into a comprehensive management system can facilitate timely interventions, ensuring that the larvae thrive and maximize their waste processing capabilities.Moreover, incorporating diverse organic substrates can also enrich the larvae's diet, leading to improved growth rates and enhanced nutrient recovery from the waste.

Reliability and Effectiveness of K-NN Classification

The classification performed by the K-NN algorithm not only reflects the actual state of the environment but also provides a solid basis for operational decision-making. The algorithm is capable of processing inputs from multiple sensors and producing clear and accurate classification outputs. By classifying environmental conditions into optimal, moderate, and poor categories, the system provides vital information needed for rapid intervention, such as resetting environmental conditions or adjusting larval feeding (Nuraini et al., 2023). The success of this classification also indicates the potential of the K-NN algorithm for similar applications in other fields that require close environmental monitoring, as its non-parametric nature allows it to adapt to various datasets without assuming data distribution (Boyko et al., 2023).

The K-NN algorithm's role in this system is particularly noteworthy. It does not merely reflect the current environmental status but enhances decision-making capabilities by classifying conditions into optimal, moderate, and poor categories. This classification empowers system managers to implement quick adjustments that are pivotal in maintaining the necessary balance within the larvae's habitat (A. Odilov et al., 2024). The algorithm's ability to synthesize data from multiple sensors and yield accurate outputs quickly demonstrates its applicability beyond this specific use case, suggesting its potential utility in other critical areas requiring detailed environmental surveillance (Saleh et al., 2024). The success of the K-NN classification in this context also opens avenues for its application in diverse fields that could benefit from precise environmental monitoring and adaptive control systems (Rydhmer et al., 2024). Moreover, the integration of machine learning techniques with real-time data analysis could further enhance the responsiveness of these systems, allowing for proactive measures to be taken before environmental conditions reach critical thresholds. Such advancements could lead to improved disaster response strategies, optimized resource management, and more effective conservation efforts, ultimately contributing to a more sustainable interaction with our environment.Additionally, the collaboration between interdisciplinary teams will be crucial in developing these technologies, ensuring that ecological, social, and economic factors are all considered in the decision-making process.

Impact of Computation Time and Data Transmission

The system's ability to process and deliver data in approximately 1.5 seconds per cycle is a significant technical achievement. This speed is crucial in operations that require rapid response to maintain or restore ideal operational conditions. The rapid delivery of data via Firebase demonstrates how modern cloud technology can be integrated with IoT to ensure that data is not only quickly processed but also easily accessible to users from any location (Kumar et al., 2023). This increases the ability to better monitor and control the biodegradation process, giving managers the flexibility to make decisions based on up-to-date data (Tarrés-Puertas et al., 2023).

Moreover, the efficiency of the system in processing and transmitting data in about 1.5 seconds significantly enhances its utility in operational environments that demand rapid responses. The integration of Firebase for data handling illustrates the effective use of cloud technologies in streamlining data accessibility and management. This capability ensures that decision-makers can access real-time data from anywhere, making it possible to swiftly address any deviations from the desired environmental conditions (Hiremath et al., 2023). The quick data turnaround is crucial in scenarios where delays can lead to inefficiencies or potential harm to the biological processes taking place, particularly in tightly controlled environments like those necessary for organic waste decomposition using larvae (Alkhatib et al., 2024).

Implications for Waste Management and Sustainable Agriculture

The results of this study have broad implications. First, the developed system offers a model for improving organic waste management that can be more widely applied, not only in the agricultural industry but also in urban areas where organic waste management is a serious problem (Vadivel et al., 2024). Second, the use of *Hermetia illucens* larvae as waste decomposers in a well-controlled system offers a sustainable and biological method that reduces the use of hazardous chemicals (Bonala et al., 2024). Third, this study also paves the way for further research on how IoT technologies and machine learning algorithms such as K-NN can be optimized for other environmental applications (R. Ponni et al., 2024; Wang et al., 2024).

The broader implications of this study for waste management and sustainable agriculture are profound. The development of an IoT-based system as modeled in this study offers a scalable solution to managing organic waste more effectively across both urban and agricultural settings (Chandre et al., 2024). The use of *Hermetia illucens* larvae as a biological agent for waste decomposition under controlled conditions not only mitigates the reliance on chemical processes but also promotes a sustainable approach to waste management (Tirtawijaya et al., 2024). This system's ability to monitor and adjust environmental conditions accurately also reduces the ecological footprint of waste processing operations, aligning with broader environmental sustainability goals (Deguara et al., 2024; Nishan et al., 2024).

4. Research Implications

Practical Implications

This study successfully developed and tested an intelligent system based on the Internet of Things (IoT) designed to automatically monitor and classify the environmental conditions of Hermetia illucens larvae. This system uses a combination of sensors to measure important parameters such as temperature, humidity, and media height. Data obtained from the sensors are processed using the K-Nearest Neighbor (K-NN) algorithm, which is able to classify the environmental conditions of the larvae into three categories: optimal, moderate, and poor. The level of accuracy achieved by this system is 87.7%, which shows the effectiveness of the K-NN algorithm in managing real-time data. The results of this study prove that IoT and K-NN can be effectively integrated into an environmental monitoring system that supports the biodegradation process of organic waste more efficiently and accurately.

This IoT-based intelligent system contributes greatly to simplifying the management of organic waste. With continuous automatic monitoring, waste managers can make faster and more precise decisions in maintaining optimal environmental conditions for larvae. This has a direct impact on the effectiveness of the waste decomposition process, which can ultimately increase biodegradation efficiency. Not only that, this system also reduces dependence on manual monitoring which is often prone to errors and takes a lot of time and effort. The use of IoT in environmental management like this opens up great opportunities for application in other sectors that require intensive monitoring of environmental parameters.

The contribution of this technology is not only limited to technical aspects but also creates positive social and economic impacts. Automation in environmental monitoring reduces operational costs, especially in terms of reducing the need for manual labor. This technology can also be used to empower local communities, especially in the agricultural and livestock sectors, which focus on the use of Hermetia illucens larvae as alternative feed. With the technology that ensures optimal conditions for the growth of larvae, the productivity of the sector can be increased. This ultimately has a positive impact on the local economy, especially for farmers and livestock breeders who can utilize high-quality alternative feed from the biodegradation of organic waste.

In terms of environmental sustainability, the implementation of this system supports global efforts to reduce the negative impact of waste on the environment. By maximizing biodegradation efficiency, this system helps reduce the amount of waste that ends up in landfills, as well as reducing greenhouse gas emissions such as methane produced from unmanaged organic waste. This emission reduction is critical in efforts to address worsening climate change. In addition, the compost produced from the biodegradation process can be used to improve soil quality, supporting more sustainable agricultural practices.

Overall, this study shows the great potential of the integration of IoT and classification algorithms such as K-NN in supporting more efficient and sustainable waste management. This system provides extensive benefits, both in technical, social, economic, and environmental terms. In the future, further research can be focused on the development of more sophisticated algorithms to improve classification accuracy as well as on expanding the application of this system in various other industrial sectors that require strict environmental monitoring. With the results that have been achieved, this system has the potential to be applied on a wider scale and become part of the global solution in waste management and environmental sustainability.

Theoretical Implications

This study makes a significant contribution to the literature in the field of IoT technology and the K-Nearest Neighbor (K-NN) algorithm, especially in its application in the environmental management sector. The integration of IoT and K-NN technology in this study demonstrates how automated monitoring can produce accurate classifications for dynamic environmental conditions. This system not only offers a practical solution but also forms a foundation for further development in technology-based environmental management theory. With empirical evidence that the K-NN algorithm is effective in classifying environmental data, this study opens up opportunities to explore other classification methods, such as Support Vector Machines or Neural Networks, in the context of natural resource management. In a broader context, this study shows that IoT technology can act as a catalyst in advancing sustainable approaches to waste management, which can be adopted in various other industrial sectors.

In addition, this study also deepens the understanding of how classification algorithms, such as K-NN, can be applied in complex environmental management systems. This algorithm has proven effective in classifying the environmental conditions of Hermetia illucens larvae into relevant categories, namely optimal, moderate, and poor. This opens up space for academics to conduct comparative studies between different algorithms and how these methods can be adapted according to specific needs in the field. This study also strengthens the theory of automation in environmental management, where sensor technology and classification algorithms can be seamlessly integrated into one system to minimize human intervention. This theory is relevant in various sectors, from agriculture to manufacturing, which require strict environmental control to ensure operational efficiency.

Within the framework of sustainable management, this study also broadens the understanding of the role of IoT technology in improving waste management efficiency. By using a real-time monitoring system, waste managers not only obtain data instantly but are also able to analyze environmental conditions comprehensively. This supports the development of a broader theory of technology adaptation in a dynamic and flexible management system. In the future, this study can be an important reference for academics and practitioners who want to combine similar technologies to manage other complex ecosystems that require close monitoring. Thus, this study contributes to the formation of new theories in technology-based environmental management that focus on sustainability and automation.

This research also has a significant social impact, especially in increasing public awareness of the importance of more effective organic waste management. With technology that can provide real-time data on environmental conditions, people, both at the household and industrial levels, can better understand their role in preserving the environment. The application of this technology allows users to actively participate in waste management, because they can see directly the impact of their actions on environmental conditions. This can encourage more positive behavioral changes towards the environment, where people become more proactive in reducing waste and utilizing resources more efficiently. Ultimately, this system can be an educational tool that encourages people to care more about waste management and environmental sustainability.

In addition to increasing public awareness, this technology also has a positive impact on labor efficiency in the waste management sector. With automatic monitoring, manual supervision that requires a lot of labor can be reduced. This allows waste managers to focus more on other strategic tasks, such as planning and developing better waste management innovations. In the long run, this automation not only reduces operational costs but also creates opportunities for workers to improve their skills in technology and environmental management. This system can be a model for application in other sectors that require high operational efficiency with a better trained workforce and focus on innovation.

This technology can also play a role in empowering local communities, especially in rural areas involved in organic waste management. Local communities that previously used traditional methods can now adopt modern technologies that are more efficient and effective. With access to IoT-based monitoring systems, they can increase their capacity and productivity in managing organic waste, which in turn can improve the quality of life and local economy. This technology provides access to innovative solutions that may have previously been out of reach for rural communities, strengthening their position in the agricultural and environmental management value chain.

Economically, this research provides various benefits, especially in terms of operational cost efficiency in organic waste management. With an IoT-based automatic monitoring system, waste managers can reduce their dependence on manual labor, which means significant savings in terms of operational costs. Waste management that previously required intensive monitoring can now be done automatically with high accuracy. This certainly provides long-term benefits, especially for industries operating on a large scale, where reducing operational costs is a key factor in maintaining profitability. With lower operational costs, industries can allocate their resources to other areas that require further innovation and development.

Furthermore, this system can also increase productivity in the agricultural and livestock sectors, especially in the use of Hermetia illucens larvae as alternative feed. With accurate monitoring of the environmental conditions of the larvae, farmers or breeders can ensure that the larvae grow in optimal conditions, which ultimately produces high-quality feed products. This product can be a source of affordable and sustainable protein, which can be sold at competitive prices in the market. In the long term, the application of this technology will not only increase production efficiency but also open up opportunities for the alternative feed industry to develop.

This research also opens up new opportunities for business models in the organic waste management sector. This technology can be adopted as a service offered to industries or communities that require efficient environmental monitoring solutions. IoT service providers can leverage this technology to offer continuous environmental monitoring tailored to customer needs. This business model will not only benefit the waste management industry but also create new market opportunities for more environmentally friendly technology-based services. With the growing awareness of better waste management, the potential for this market continues to increase.

From an environmental perspective, this research has the potential to make a significant impact in reducing the environmental footprint of organic waste. With technology that can monitor and manage waste more efficiently, the amount of organic waste that ends up in landfills can be drastically reduced. This system allows waste management to be more measurable and responsive, thereby reducing the risk of waste accumulation that can cause pollution. In addition, with less organic waste being thrown away, greenhouse gas emissions such as methane, which are usually produced by decomposing organic waste, can be reduced. This is in line with global efforts to reduce greenhouse gas emissions and combat climate change.

Better management of organic waste also has a positive impact on soil and water quality. Properly processed organic waste can produce compost that is useful for improving soil structure and increasing its fertility. The use of this compost is not only beneficial for sustainable agriculture, but also helps prevent soil erosion and maintain the balance of nutrients in the soil. In addition, by reducing waste accumulation, the risk of groundwater contamination by hazardous compounds produced by organic waste can be minimized. Thus, this system contributes to the protection of natural resources that are very important for environmental sustainability.

This technology also supports long-term sustainability by integrating environmentally friendly solutions into waste management. This automated system allows organic waste management to be carried out in a more responsible and efficient manner, which not only reduces the negative impact on the environment but also extends the life cycle of the resource. In a broader context, this system can be part of a sustainability strategy implemented by various industries that want to reduce their environmental footprint. Therefore, this research plays a role in promoting sustainable waste management practices.

5. Conclusion

This study successfully developed and tested an IoT-based intelligent system to monitor and classify the environmental conditions of Hermetia illucens larvae. The system integrates sensors to monitor temperature, humidity, and media height where the larvae grow. The K-Nearest Neighbor (K-NN) algorithm processes the data and classifies it into three categories: optimal, moderate, and poor. Testing showed the system achieved an average accuracy of 87.7%, effectively classifying environmental conditions and providing valuable information for optimizing the biodegradation of organic waste.

The study highlights that IoT and K-NN technologies can be integrated into an automated, real-time monitoring system. This reduces reliance on manual labor while providing faster and more accurate data. The system allows users to make timely decisions in maintaining optimal conditions for larval growth, which is particularly important for managing organic waste that requires continuous monitoring for effective biodegradation. Applying this system on a larger scale could support environmental monitoring in various sectors requiring intensive control.

A key contribution of the research is the application of modern technology in organic waste management, which has traditionally relied on less efficient conventional methods. By using Hermetia illucens larvae as decomposers, the study offers a more environmentally friendly solution to organic waste challenges. The combination of advanced technology with a natural approach, through the use of larvae, provides a dual benefit: reducing the waste processing burden while producing valuable by-products such as organic animal feed. This makes the system applicable in agriculture and livestock sectors as a sustainable waste management solution.

Beyond technical contributions, the research presents positive social and economic impacts. The automation of environmental monitoring reduces operational costs, particularly by minimizing the need for manual labor. The system also enables local communities, particularly those involved in organic waste management, to adopt more efficient technology. This could empower rural communities, increasing their capacity for productive waste management. Economically, the study opens opportunities for new business models focused on providing IoT-based environmental monitoring services.

In conclusion, the integration of IoT and K-NN in environmental monitoring offers an efficient and effective solution for managing organic waste. The system provides accurate, real-time data and delivers significant social and economic benefits. Its high accuracy and easy access via mobile applications make it adaptable to various sectors, including agriculture, animal husbandry, and waste management. Future developments should focus on scaling the system and enhancing classification algorithms to further improve accuracy and responsiveness. This research lays a solid foundation for implementing IoT-based technology to support environmental sustainability through smarter, more responsible waste management.

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