Journal Of Biology Education Research (JBER)
Vol 6(1) 2025 | ISSN: 2774-7859
DOI: 10.55215/jber.v6.i1.18

https://journal.unpak.ac.id/index.php/jber

Monitoring CO_2 Levels and Total Volatile Organic Compounds in Tofu Waste Composting Process Using IoT-Based Maggot Larvae

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Received: 20 Desember 2024. Revised: 20 Februari 2025 Accepted: 1 April 2025

Abstract

The increasing volume of waste poses significant environmental and public health risks if not properly managed. The management of unprocessed waste may be initiated at the household level by applying principles of the circular economy. This study aims to investigate the integration of bioconversion technology using Black Soldier Fly (BSF) larvae with an IoT-based air quality monitoring system for tofu dregs waste management. A microcontroller-based device was developed to monitor and control humidity, carbon dioxide (CO_2), and Total Volatile Organic Compounds (TVOCs) using sensors and an adsorption-based scrubber system. The results indicate that CO_2 levels decreased from 1470–1747 ppm to 400–483 ppm, while TVOC levels were reduced from 163–346 ppb to 0–6 ppb after treatment, significantly improving air quality and minimizing odor emissions. The combination of BSF larvae-assisted bioconversion and automated emission control demonstrates a highly effective and sustainable approach to organic waste processing, reducing environmental pollution and generating valuable byproducts for economic utilization. This system offers a scalable solution for future applications in circular economy-based waste management. In conclusion, this system offers a scalable solution for future applications in circular economy-based waste management.

Keywords: CO_2; IoT; maggot; TVOC

INTRODUCTION

The continuously increasing volume of waste, if not properly managed, can negatively impact environmental quality and public health. Local governments must take preventive measures to mitigate the adverse effects of these negative externalities in the form of waste. This can be achieved by providing education, assistance, and outreach programs focused on the principles of reducing, reusing, and recycling (Khairunisa & Safitri, 2020). Development that prioritizes environmental quality will foster inclusive well-being for both society and the environment. Managing unprocessed waste can begin at the household level by adopting a circular economy approach. This approach represents a practical application of the green economy concept, aimed at achieving sustainable development by integrating economic growth with environmental protection (Kasztelan, 2017).

The circular economy is fundamentally based on the 3R principles (Reduce, Reuse, Recycle), emphasizing optimal production by efficiently utilizing natural resources. It aims to minimize environmental exploitation, reduce pollution, lower emissions and waste, and promote the implementation of sustainable practices (Sørensen, 2018; Strielkowski, 2016). The concept of a circular economy can significantly reduce waste generation by promoting environmentally friendly product designs and ensuring careful processes in industries that implement the closed-loop system method

(Bocken et al., 2016). In the long term, resource production from waste can reduce emissions by up to 70%, increase employment by 4%, and significantly decrease waste volume (Velenturf et al., 2021). The implementation of a circular economy can enhance environmental resilience, improve social welfare, reduce environmental degradation, foster the creation of new product added value, and drive green economic growth aligned with the goals of sustainable development (Bocken et al., 2016; Kasztelan, 2017; Sørensen, 2018; Strielkowski, 2016; Velenturf & Purnell, 2021).

Implementation of the circular economy concept by adopting variables such as per capita urban waste generation, urban waste recycling rates, packaging waste recycling rates by type, organic waste recycling rates, and electronic waste recycling rates, it is possible to promote high-quality, sustainable economic growth and inclusive GDP growth. At the same time, this approach reduces natural resource consumption and ensures greater environmental protection (Busu & Trica, 2019; Sverko Grdic et al., 2020). Waste has become a significant issue as the population grows, requiring effective management from temporary disposal sites (TDS) to final disposal sites (FDS). Additionally, proper waste processing demands suitable technology to ensure that the processed products do not generate new waste. In the era of Industry 4.0, the adoption of digital technology has emerged as an innovative solution for waste management. The Internet of Things (IoT) has proven to enhance environmental monitoring efficiency by providing real-time data that can be accessed remotely, enabling rapid responses to changes in environmental parameters. Previous studies have indicated that the implementation of IoT in waste processing improves the effectiveness of gas emission control and supports the sustainability of the circular economy (Jayaraman et al., 2016). Therefore, this study develops an IoT-based monitoring system to control CO_2 and TVOC emissions in the composting process of soybean pulp using Black Soldier Fly (BSF) larvae.

Organic bioconversion technology, such as maggot cultivation, offers a promising solution for organic waste management. Black Soldier Fly (BSF) larvae are highly effective in degrading waste, outperforming other insects, and are safe for human health as they are not disease vectors. The byproducts of BSF bioconversion include BSF eggs, maggots, kasgot (bioconversion residue), which can serve as growing media for vegetables, and leachate, a liquid derived from the rearing media, which can be used as organic liquid fertilizer. This bioconversion program not only addresses environmental challenges through organic waste reduction but also enhances the welfare of maggot farmers, fisheries, and organic agriculture. Additionally, BSF larvae can reduce organic waste volume by up to 50% daily, with each kilogram of larvae capable of degrading 3–4 kg of organic waste per day (Rukmini et al., 2020). The high nutritional content of maggots also makes them an alternative protein source for livestock and aquaculture, further supporting sustainable food production systems (Rukmini et al., 2020).

The processing of organic waste, such as tofu waste, is carried out using Black Soldier Fly (BSF) larvae, which consume organic waste and convert it into various insect protein products. Maggots can be used as natural feed for livestock, while the processed organic matter is turned into fertilizer for agriculture. The maggots hatch from eggs after a 4-day incubation period, and the larvae, which grow to about 30 cm long and 6 cm wide, continue feeding throughout their life cycle of approximately 14 days. Kitchen waste, manure, and garden waste are preferred food sources for BSF larvae. This method proves to be highly effective, both in terms of conversion rate (up to 50%) and the valuable products produced from the conversion. PT Biomagg Sinergi Internasional is a company providing responsible and reliable organic waste management solutions since 2017. The company uses bioconversion technology to process organic waste, transforming it into economically valuable products by using Black Soldier Fly (BSF) larvae that consume organic waste and convert it into insect protein. To date, the company has processed 3,104 tons of organic waste. In this study, we received supervision from PT Biomagg Internasional in terms of procuring BSF larvae seeds and guidance on other technical issues. The waste sorted for maggot feed needs to be carefully selected. If organic waste is not properly sorted, maggots will produce foul odors, contributing to air pollution. This can be confirmed by high levels of Volatile Organic Compounds (VOC). High VOC concentrations are difficult to control manually and quickly, so a sensor-equipped device capable of measuring and adsorbing VOCs and CO2 in the maggot breeding environment is needed. Based on this issue, the decision was made to design a microcontroller-based device that can measure and absorb VOCs and CO2 in the maggot breeding facility.

METHOD

The equipment used includes: First we prepare a set of maggot breeding sites. This tool consists of 3 plastic containers with dimensions of 25x50x80 cm. These three containers are placed on each supporting layer made of light steel. Next, we prepare 1 set of air pollution control equipment, a set of TVOC sensors and CO_2 sensors. The material used in this test was tofu industry waste dregs, each weighing around 5 kg and the surface of the waste was leveled. The next stage is adding maggot larvae to the surface of the waste. In a composting device using maggots, the entire plastic container is covered with plastic wire to prevent unwanted living creatures from entering. Next, the air pollution control device and its sensors can be turned on. Every day, stirring is carried out to maximize the waste processing process. In Figure 1 you can see the design and equipment of the maggot larvae breeding room.

Figure 1. The design and equipment space

The circuit diagram serves as the blueprint for the equipment model to be designed. The microcontroller module subsequently sends the data from sensor readings and relay conditions to an LCD display and to Firebase as a database. Below is the circuit schematic for the development of this equipment on Figure 2. The image was created with the fritzing program is an open-source software tool designed to support designers.

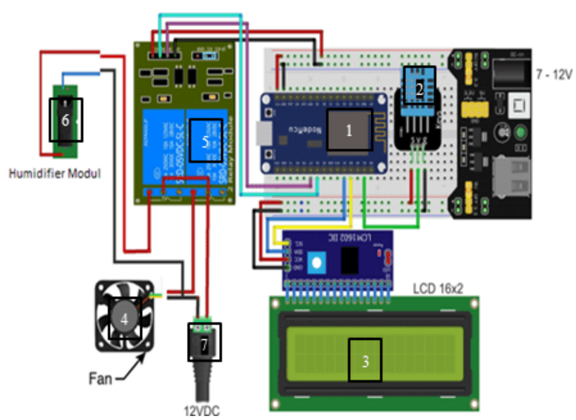

Figure 2. Initial Design of the Air Monitoring Device in the BSF Breeding Space

Information:

1. Microcontroller Board (ESP32/Arduino)
2. Sensor DHT (Temperature and Humidity)
3. LCD 16x2
4. Fan

5. Relay Module
6. Humidifier Module
7. Power Supply (7-12V)

Maintenance of BSF Larvae . The initial trial involved the full maintenance of Black Soldier Fly (BSF) larvae over one complete life cycle, including larva, mature larva, prepupa, pupa, and adult fly stages. The duration of this process was approximately 45 days. Throughout this period, maintenance was carried out according to the standard operating procedure (SOP) provided by *PT. Biomagg Sinergi Internasional.* During the maintenance period, temperature, humidity, and VOC levels in the air were monitored to obtain data trends throughout the process. The ideal temperature is between 24°C to 30°C. If it is too hot, the larvae will leave their food source to look for a cooler place. If it is too cold, the larvae's metabolism will slow down. A shady environment and away from sunlight, if the food source is exposed to light, the larvae will move to deeper layers of the food source to avoid the light. The ideal humidity for maggot growth lies between 60% and 90%, which helps the larvae digest their feed. These sensors are connected to a cloud-based database via WiFi, enabling remote monitoring and data-driven analysis using an ESP32 microcontroller. This system is designed to support a cyber-physical systems approach in Industry 4.0, where IoT sensors optimize gas emission monitoring through automation and real-time data integration (Alharthi et al., 2019; Bigiotti et al., 2025; Campo et al., 2018; Elsisi et al., 2021; Hasan & Ahammed, 2021; Jalinder Jadhav et al., 2024; Lee et al., 2014; Mistry et al., 2024; Munsamy & Telukdarie, 2018; Patel et al., 2023; Qian et al., 2022; Suresh et al., 2023). Additionally, integration with the scrubber and adsorbent system ensures that the collected data can be utilized for more effective decision-making in organic waste management. As a comparison, sensors with the same specifications were also installed without the presence of BSF larvae or processed solid waste, serving as baseline data. Another treatment involved monitoring and maintenance using the same method but without the odor and CO_2 control system.

Table 1. Experimental plan for ambient air quality monitoring

Code	**Treatment**	**Observed Parameters**
A	Baseline (Monitoring equipment without pollution control)	CO_2, odor, TVOC
B	Standard Maintenance (Monitoring equipment in maintenance room without pollution control equipment)	CO_2, odor, TVOC
C	Maintenance with Design Tools (Tools for monitoring and controlling pollution in the maintenance room)	CO_2, odor, TVOC

Data Analysis and Design Finalization. The data collected from the designed device was processed using data analysis software and then compared across different treatments. Treatment A served as the baseline, measuring CO_2 levels and odor conditions in the maintenance environment. Treatment B involved monitoring the maintenance conditions without intervention from the automatic humidity and odor control system. Treatment C included monitoring the maintenance environment using the designed device. The results from these treatments were analyzed to evaluate the effectiveness of the device and refine the final design.

RESULT AND DISCUSSION

The composting facility, equipped with air pollution control devices (APCD) and sensors, was utilized to process various organic waste types, including coconut pulp, tofu dregs, and vegetable waste. The decomposition of organic waste by Black Soldier Fly (BSF) larvae is known to generate volatile organic compounds (VOCs) and carbon dioxide (CO_2) emissions due to microbial activity . To mitigate these emissions and optimize the composting process, it is essential to maintain air quality control within the facility. To minimize VOC emissions, the air surrounding the composting chamber was extracted using a pump and directed into the APCD, which consists of an adsorber and a scrubber system. The adsorber contained a mixture of ginger charcoal and zeolite, chosen for their high porosity and alkaline properties, which enhance adsorption efficiency. Meanwhile, the wet scrubber system, designed to remove airborne pollutants, operated by using a liquid medium to chemically absorb or neutralize contaminants. This approach effectively reduced gas emissions, improving overall air quality during the composting process (Amrul et al., 2022; Cheremisinoff & Rosenfeld, 2010; Kumar et al., 2018).

The APCD system utilized four recycled plastic drums, each with a 60-liter capacity. The first two drums functioned as a double wet scrubber, connected in series through PPC pipes and spray nozzles to maximize contact between polluted air and water, facilitating the removal of harmful particles. The third drum contained foam filters, zeolite stones, and coral stones as filtration media, ensuring the removal of residual contaminants before the scrubber water was collected in the final holding tank. The zeolite material, sourced from Sukabumi, was selected due to its abundant microporous and macroporous structures, which enhance adsorption capacity. The design and implementation of this air pollution control equipment are illustrated in Figure 3.

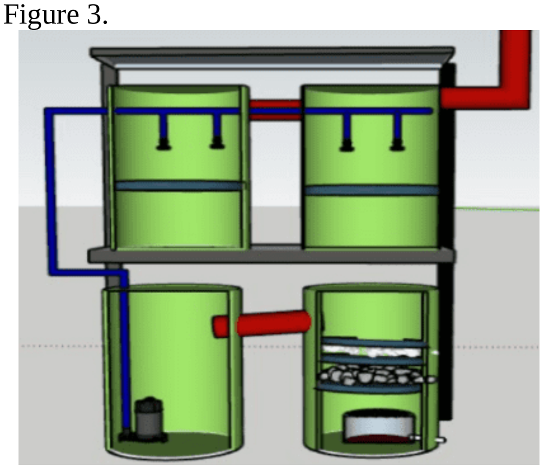

Figure 3. Design and Equipment of APCD

The monitoring process for tofu dreg composting was conducted over five days (Figure 4), with CO_2 and TVOC levels measured at various time intervals. On the first day, sensors were placed near the composting container for the initial 20 minutes, followed by another 20-minute measurement after the emission air passed through the APCD system. The results indicated that initial CO_2 levels ranged from 1470 to 1747 ppm, while TVOC concentrations were recorded between 163 and 346 ppb. The high VOC values correspond to intensive microbial decomposition, leading to significant emissions. After 20 minutes, VOC levels decreased by over 85%, while CO_2 levels dropped by more than 62%. The final CO_2 and TVOC levels after APCD treatment ranged between 400–560 ppm and 13–35 ppb, respectively. Further monitoring revealed additional reductions, with CO_2 levels stabilizing at 400–483 ppm and TVOC levels nearing 0–6 ppb. These findings highlight the significant role of the APCD system in reducing VOC and CO_2 emissions, with VOCs experiencing the most drastic reduction due to adsorption and scrubbing mechanisms.

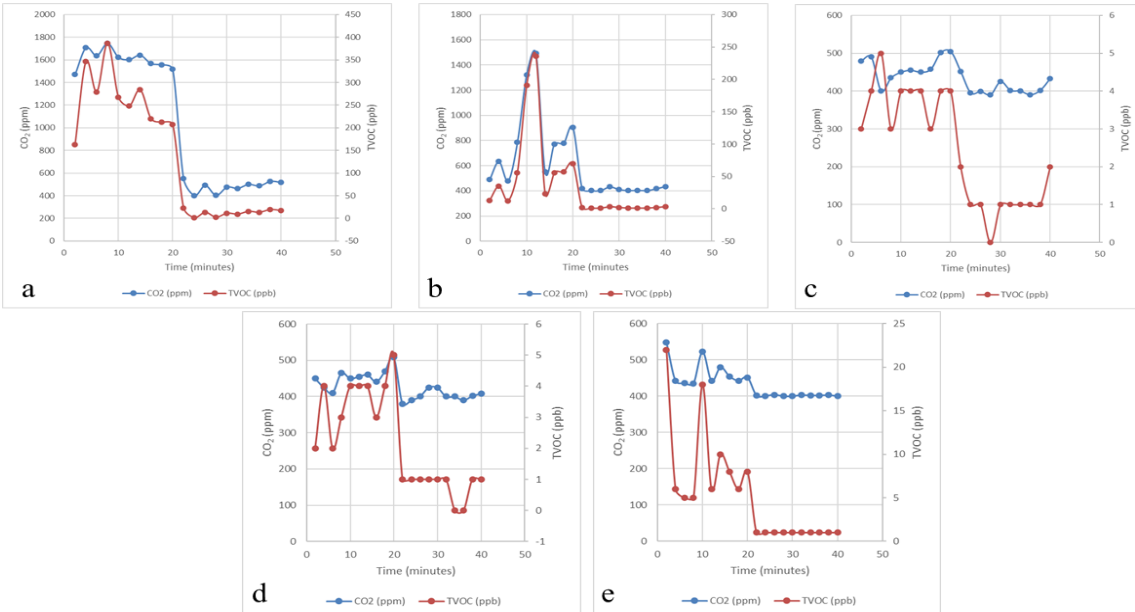

Figure 4. Monitoring of CO_2 and TVOC Levels During Tofu Waste Composting Over Five Days (a. first, b. second, c. third, d. fourth, e. fifth). Real-time monitoring of CO_2 (ppm) and TVOC (ppb) levels during the composting process over five days. The graphs illustrate the reduction in gas emissions following the activation of the air pollution control device (APCD).

The concentration of CO_2 and TVOC were fluctuated in second day, that ranged between 480–1492 ppm and 12–236 ppb, respectively. The variations were attributed to external environmental factors, such as wind direction and humidity fluctuations. However, after 20 minutes of APCD activation, both CO_2 and VOC levels decreased, confirming the efficiency of the ginger charcoal-zeolite adsorbent and wet scrubber system in gas reduction. By the third day, emissions exhibited greater stability, with CO_2 levels at 400–505 ppm and TVOC concentrations at 3–5 ppb, demonstrating the system's consistency in air quality improvement. On the fourth day, a similar pattern was observed, though slight decreases in CO_2 and TVOC levels were recorded, indicating that microbial activity in the composting process was still ongoing (He et al., 2020). The measured CO_2 and TVOC levels on this day were 416.67 ppm and 8.43 ppb, respectively. By the fifth day, CO_2 and TVOC concentrations were notably lower, averaging 408.33 ppm and 1.5 ppb, respectively. The consistent reduction in emissions indicates that the composting process had reached a more stable and controlled phase, demonstrating the effectiveness of IoT-based air quality monitoring in tracking gas emissions over time. These results are in line with previous research, which found that VOCs are most prominent during the initial stages of composting when high-fat and protein-containing organic matter, such as tofu and coconut dregs, undergoes decomposition (He et al., 2020; Li et al., 2022; Walpajri et al., 2023).

The implementation of Black Soldier Fly (BSF) larvae in tofu waste composting significantly influenced the reduction of Total Volatile Organic Compounds (TVOCs) and carbon dioxide (CO_2) levels in the waste management environment. The data collected from real-time monitoring indicated that CO_2 concentrations decreased from an initial range of 1470–1747 ppm to 400–483 ppm, while TVOC levels were reduced from 163–346 ppb to 0–6 ppb. These findings are consistent with previous studies emphasizing the role of BSF larvae in organic waste bioconversion and its impact on air quality improvement (He et al., 2020; Michishita et al., 2023). The significant reduction in TVOCs is attributed to the metabolic activities of BSF larvae and the microbial communities associated with their gut microbiota. Research has shown that BSF larvae alter microbial populations in organic waste, reducing the presence of pathogenic and odor-producing bacteria (Li et al., 2022; Rukmini et al., 2020). The present study identified the dominance of *Lactobacillus*, *Leuconostoc*, *Bacillus*, and *Actinomycetes*, which are known to produce volatile organic sulfur compounds (VOSCs) such as dimethyl disulfide (DMDS) and dimethyl trisulfide (DMTS), contributing to odor emissions in untreated waste (Hasan et al., 2021; Suresh et al., 2023). The transformation of microbial communities through BSF intervention thus plays a crucial role in controlling the emission of these compounds. The effectiveness of BSF larvae in waste bioconversion aligns with the circular economy concept, which integrates organic waste valorization into sustainable resource utilization (Busu et al.,, 2019; Velenturf et al., 2021). Besides reducing TVOCs, BSF larvae also produce by-products such as larval biomass and compost residue (kasgot), which can be repurposed as high-protein feed and organic fertilizer (Bocken et al., 2016; Busu et al., 2019; Liland et al., 2023; Michishita et al., 2023; Viguier et al., 2021). This transformation highlights the dual environmental and economic benefits of incorporating BSF into waste management strategies.

(a) (b)

Figure 5. (a) Initial input of tofu dregs and (b) tofu dregs after decomposition

The observations on the fifth day demonstrated greater stability, indicating the completion of the composting process. Composting generates gas emissions such as CO_2 and TVOC, with concentrations fluctuating depending on the type of organic material and microbial activity. According to Li et al. (2022) research, volatile compounds (TVOC) are typically higher at the start of the composting process, particularly when organic materials rich in fats or proteins, such as tofu and coconut dregs, undergo decomposition (He et al., 2020; Li et al., 2022). The significant reduction in CO_2 and TVOC levels demonstrates the effectiveness of the IoT system in supporting gas emission monitoring and control during the composting process. With cloud-connected sensors, this system enables real-time data processing and gas emission trend analysis, forming an integral part of the smart waste management approach in Industry 4.0 (Jayaraman et al., 2016; Srisooksai et al., 2019; Sułkowska, 2021). The visual transformation of tofu dregs throughout the composting process is depicted in Figure 5.

CONCLUSION

The IoT-based emission control system successfully reduced CO_2 and TVOC concentrations to near ambient levels, reaching 408.33 ppm CO_2 and 1.5 ppb TVOC by the fifth day. The integration of Black Soldier Fly (BSF) larvae and air pollution control devices (APCDs) optimized waste decomposition, reducing odor and improving compost stability. The presence of beneficial microbes further enhanced organic matter breakdown. This approach aligns with circular economy principles, converting organic waste into high-protein feed and organic fertilizer, promoting sustainable waste management. This research is useful for the global community, especially researchers, because it can be used as a reference for further research that focuses on scalability and long-term impacts in industrial applications.

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