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Sustainable Organic Waste Reduction Using Black Soldier Fly Larvae: The Effect of Music Variation on Bioconversion Performance

Dhea Andini[1*], Bimastyaji Surya Ramadan[1], Sri Sumiyati[1]

[1] Department of Environmental Engineering, Universitas Diponegoro, Semarang, Indonesia.

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Corresponding Author:
Dhea Andini
dheaandini@students.undip.ac.id

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Abstract: Black Soldier Fly (BSF) larvae are widely recognized as a sustainable solution for organic waste reduction due to their ability to convert waste into valuable biomass. This study aimed to evaluate the effect of music variations on the bioconversion performance of BSF larvae. A laboratory experiment was conducted using five sound treatments: no music (A), random music (B), dangdut music (C), classical music (D), and metal music (E). The larvae were fed organic waste, and the observed parameters included Waste Reduction Index (WRI), Efficiency of Conversion of Digested Feed (ECD), Survival Rate (SR), and protein content. The results showed that music variations did not significantly affect all observed parameters ($p > 0.05$). However, the classical music treatment tended to produce higher WRI and ECD values compared to the other treatments. The survival rate and protein content of the larvae were relatively similar across all treatments. These findings indicate that sound exposure does not significantly affect the bioconversion performance of BSF larvae, but certain types of music may provide more favorable conditions. This study supports the application of BSF larvae in sustainable organic waste management.

Keywords: Bioconversion; Black soldier fly larvae; Music variation; Organic waste; Sustainability

Introduction

Organic waste is still one of the major environmental problems, especially in areas with increasing population and consumption. Increasing human consumption contributes significantly to the rising generation of waste (Widanti et al., 2024). Human activities are the main contributors to environmental damage, including the increasing generation of organic waste (Amin & Maritasari, 2023; Anwar et al., 2024). Data from Badan Pusat Statistik show that the population in Kendal District increased from 61.642 people in 2022 to 62.246 people in 2023, which contributes to higher waste generation. Based on data from the National Waste Management Information System (SIPSN), waste generation in Kendal Regency reached 421.36 tons/day in 2023, with organic waste as the dominant type. If not properly managed, organic waste can cause environmental pollution and negatively impact public health (Heryanti et al., 2023; Gautam et al., 2025). Poorly managed waste can have negative impacts on the environment and surrounding communities (Permatasari et al., 2023). Therefore, a more sustainable and efficient method for managing organic waste is needed. Organic waste problems continue to increase and require effective and valuable treatment methods, one of which is through bioconversion processes, where waste is not only reduced but also transformed into useful products, thereby supporting higher efficiency in waste reduction and material conversion (Armi et al., 2023). The utilization of alternative biological resources has been shown to improve efficiency and productivity in biological systems(Herliani et al., 2025).

One of the potential solutions is the use of Black Soldier Fly (BSF) larvae (*Hermetia illucens*) as bioconversion agents. BSF larvae possess active

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biological systems, including antimicrobial compounds, which support their role in organic waste decomposition (Sucipto et al., 2025). BSF larvae are known for their ability to convert organic waste into useful products such as valuable biomass such as protein and organic fertilizer, making them a promising solution for sustainable waste management (Putri et al., 2023a; Mabruroh et al., 2022; Putri et al., 2023b; Hasanah et al., 2023; Jupri et al., 2025). BSF larvae based feed can significantly contribute to poultry production efficiency (Tanjung et al., 2025). In addition, the application of BSF larvae at the community level has also shown positive impacts in managing household organic waste, indicating their potential for wider implementation in real environmental conditions (Sari et al., 2026). Previous studies have shown that their performance in reducing organic waste is influenced by several factors, such as feed type, feeding rate, larval density, and environmental conditions like temperature and pH (Albalawneh et al., 2024; Cattaneo et al., 2024; Chia et al., 2018; Ma et al., 2018). However, to further improve their performance, it is important to explore other factors that may influence their productivity, especially external environmental stimuli that are still rarely studied.

One of the external factors that can be explored is sound. Previous studies have shown that sound can influence physiological and behavioral responses in living organisms (Alworth & Buerkle, 2013). However, in insects and other invertebrates, sound is not perceived as music in the same way as in humans, but rather as mechanical vibrations detected through mechanoreceptors. These vibrations can affect feeding activity, stress responses, and development. For example, exposure to high-frequency sound (5,000 Hz) with intensities above 85 dB has been shown to act as a stress factor in *Hermetia illucens*, affecting pupation, survival, and gene expression related to immune and digestive systems (Park et al., 2013).

In addition, several studies have shown that invertebrates are sensitive to particle motion generated by sound waves, even without having a hearing system like vertebrates (Davies et al., 2024; Mankin et al., 2021; Göpfert & Robert, 2003). This means that sound, including music, can be understood as a form of vibration that may influence their biological responses. Research on aquatic invertebrates also shows that different types and intensities of sound can affect growth, survival, and behavior, although studies specifically related to music are still limited (Solé et al., 2023; Olivier et al., 2023). While studies in vertebrates, such as poultry, have shown that music can improve productivity (Cabaral et al., 2017), Its application to insects still requires further investigation. In this study, different music genres were used to represent variations in sound characteristics, since each genre has distinct patterns in tempo, frequency, and vibration. Music with more stable structures tends to produce more regular vibrations, while faster or more complex genres generate more dynamic vibration patterns (Davies et al., 2024; Göpfert & Robert, 2003; Mankin et al., 2021). These differences are expected to create different vibration stimuli that may influence the biological responses of BSF larvae (Hawkins & Popper, 2017).

Therefore, this study is important to conduct because it explores the potential of sound, represented by different music variations, as a factor that may influence the performance of BSF larvae in reducing organic waste. The novelty of this study lies in the use of different music variations as sound vibration patterns to evaluate their effect on the bioconversion performance of BSF larvae, which has not been widely studied. The performance of the larvae was evaluated based on Waste Reduction Index (WRI), Efficiency of Conversion of Digested Feed (ECD), Survival Rate (SR), and protein content.

Method

The method used in this study was a laboratory-scale experiment to obtain primary data. The experimental workflow is presented in Figure 1. The experiment began with the identification of dominant organic waste at Kendal Market, which was cabbage.

The feed used for BSF larvae consisted of a mixture of boiled cabbage and bran in a 50:50 ratio (Nur'aini & Hutasuhut, 2024). This approach was implemented based on observations, where raw cabbage was found to be less suitable due to its hard structure, making it difficult for larvae to consume, because larvae feed by hooking/scraping organic matter, softening it with enzymes, and then sucking liquid and fine particles using a pump in the pharynx/cibarium and peristaltic movements of the digestive tract (Schoofs et al., 2009; Wu et al., 2000). In addition, the use of blended cabbage resulted in excessive moisture content, causing the larvae to leave the substrate due to unfavorable conditions. Therefore, boiling was applied to soften the cabbage structure and improve feed palatability. However, boiled cabbage tends to increase the moisture content of the substrate, which may cause larvae to leave the media. Therefore, bran was added to stabilize moisture content and maintain optimal media conditions and produce the best results (Nur'aini & Hutasuhut, 2024). All feed weights were measured on a wet weight basis.

Feeding was administered at a rate of 100 mg/larva/day, based on previous studies showing that this feeding rate produces the highest larval biomass, Waste Reduction Index (WRI), and Survival Rate (SR) (Supriyatna & Putra, 2017; Aziz et al., 2024; Rahmawati

et al., 2024). Each reactor contained 200 larvae aged 8 days. At this stage (approximately 3–4 cm in size), BSF larvae are already capable of effectively reducing organic waste (Ambrawati, 2022). Therefore, each reactor received 20 g of feed per day (10 g cabbage and 10 g bran) for 14 days. The total feed per reactor during the experimental period was 280 g (140 g cabbage and 140 g bran). Feeding and measurements were conducted every 24 hours.

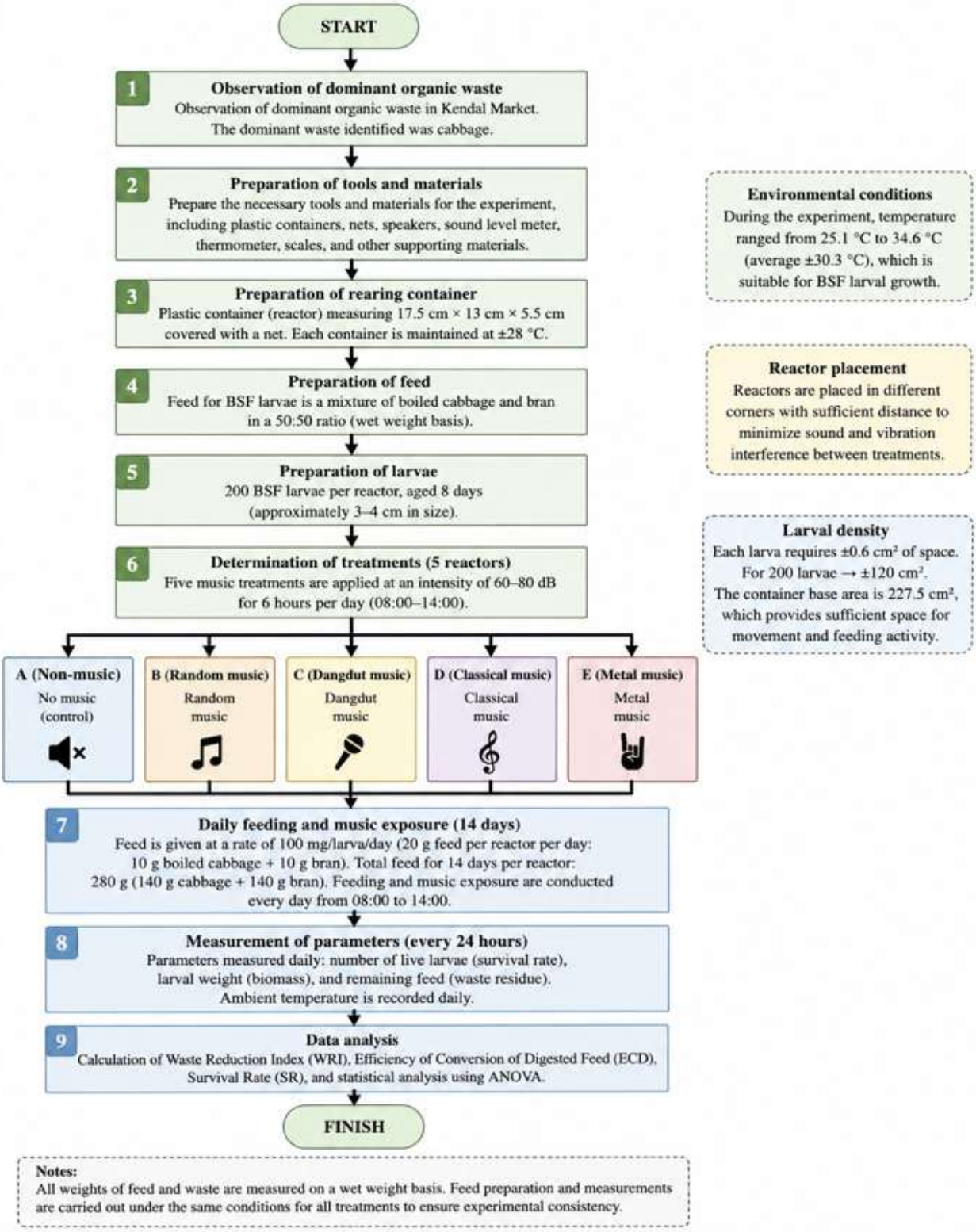

Figure 1. Experimental flowchart

Figure 2. Cabbage waste at Kendal market

Figure 3. Feed weighing

The experiment consisted of five reactors representing different music treatments: non-music (A), random music (B), dangdut music (C), classical music (D), and metal music (E). All treatments were applied at an intensity of 60–80 dB for 6 hours per day (08:00–14:00). The music intensity was controlled within this range to avoid excessive stress and ensure safe exposure conditions for the larvae, as reported by Zhao et al. (2023). The exposure duration was based on Wilson et al. (2011) music was applied in the morning because BSF larvae begin activity at around 08:30 and reach peak activity at approximately 11:00 (Rudiatin et al., 2023). Therefore, the timing of exposure was adjusted to align with larval active periods to maximize the potential effect of music stimulation on performance.

To avoid interference between treatments, each reactor was placed at different corners of the experimental setup with sufficient distance between units (approximately more than 2 meters). Music exposure was applied at an intensity of 60–80 dB. Under these conditions, the resulting vibrations have the highest intensity at points closest to the source, so the main effect is received by the larvae in each respective treatment. However, based on the principles of sound wave propagation, vibrations can still travel through air and solid media such as tables or floors, although their intensity decreases with increasing distance (Kinsler et al., 2000; Bies & Hansen, 2009; Beranek & Mellow, 2012). With a distance of more than 2 meters between reactors, vibration exposure in other treatments is expected to be at relatively low intensity, thereby minimizing the potential for interference between treatments. All reactors were maintained under the same environmental conditions to ensure experimental consistency. Although complete sound isolation was not achievable under laboratory conditions, this setup was designed to minimize interference to a negligible level. This limitation is acknowledged and considered in the interpretation of the results.

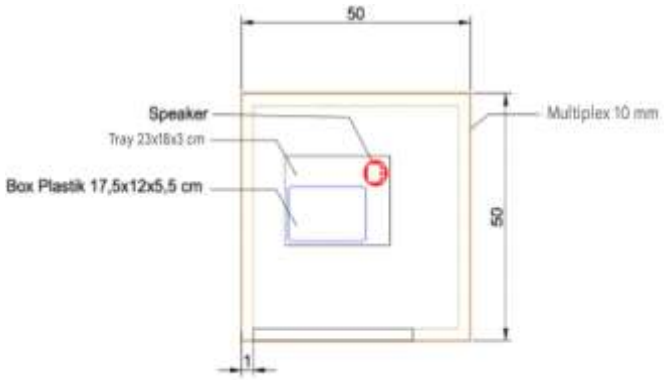

Figure 4. Reactor design 50*50*50 cm

The reactor design was based on the concept proposed by Lalander et al. (2020), who investigated process efficiency and ventilation requirements in BSF larvae composting systems. In their study, a plastic container covered with a net was used to ensure proper aeration and prevent larval escape, with approximate dimensions of 22.1 cm × 17 cm × 11 cm. Lalander et al. (2020) also utilized a comparable number of larvae per experimental unit, including the use of 200 larvae under controlled conditions. Each reactor contained 200 larvae. Larval density was determined based on the assumption that each larva requires approximately 0.6 cm² of space. Therefore, 200 larvae require about 120 cm². The container used in this study has a base area of 227.5 cm², which exceeds the minimum requirement. This larger space was intentionally provided to reduce larval competition and support optimal movement and feeding activity.

Environmental conditions, particularly temperature and feed availability, are important factors influencing the efficiency of organic waste reduction by BSF larvae

(Rofi et al., 2021). During the experiment, the recorded temperature ranged from 25.1°C to 34.6°C, with an average of approximately 30.3°C. This range is considered suitable for BSF larval growth. Kahar et al. (2020) reported that the optimal temperature for BSF rearing is 29–31°C. In addition, Chia et al. (2018) stated that BSF larvae can grow optimally within a range of 31.3°C to 36°C depending on feed type, while Harnden & Tomberlin (2016) reported that rearing at around 32°C tends to produce higher larval biomass compared to lower temperatures.

Waste Reduction Index (WRI) is a parameter used to measure the ability of BSF larvae to reduce organic waste mass. According to Zulkifli et al., (2023) WRI describes the efficiency of BSF larvae in reducing organic waste; a higher WRI value indicates a better decomposition ability of the waste. Waste Reduction Index formula (Chapagaee, 2026):

$$\mathrm{WRI} = \frac{\mathrm{W} - \mathrm{R}}{\mathrm{t}} \times 100 \quad (1)$$

Where :
- W : Total initial feed (waste) (g)
- R : Residual feed (waste) (g)
- WRI : Waste Reduction Index (%/day)
- t : Total time larvae eat waste (day)

Furthermore, to determine the significant differences in results from the 5 treatments, the researcher used the ANOVA method to process the data.

Efficiency of Conversion of Digested Feed (ECD) is a parameter used to measure the efficiency of BSF larvae in converting digested food into body biomass. According to Mahmood et al. (2021) ECD reflects the effectiveness of the BSF larvae's metabolic processes. The higher the ECD value, the more efficiently the BSF larvae utilize feed nutrients for growth. The Efficiency of Conversion of Digested Feed (ECD) formula was used to calculate the efficiency of feed conversion that can be digested by larvae (Chapagaee, 2026):

$$\mathrm{ECD} = \frac{\mathrm{B}}{(\mathrm{I} - \mathrm{F})} \times 100 \quad (2)$$

Where :
- ECD : Efficiency of conversion of digested feed (%)
- B : Larval weight gain during the larval feeding period (g), obtained by subtracting the final weight from the initial larval weight (g)
- I : Total feed (waste) input (g)
- F : Residual feed remaining in the substrate after the feeding period (g)

Survival Rate (SR) is a parameter used to measure the survival rate of BSF larvae during the observation period. According to Schreven et al., (2022) SR reflects the ability of larvae to survive under environmental conditions during treatment. The higher the SR value, the greater the proportion of larvae that can survive during treatment, thus indicating the level of tolerance and adaptation of larvae to treatment conditions. The SR (Survival Rate) formula is used to determine the survival success of BSF larvae (Vodounnou et al., 2024):

$$\mathrm{SR} = \frac{\mathrm{y}}{\mathrm{z}} \times 100 \quad (3)$$

Where:
- SR : Survival Rate (%)
- y : Total number of larvae surviving at the end of the study (individuals)
- z : The total number of larvae alive at the start of the study (individuals)

Protein content is a parameter used to assess the quality of BSF larval biomass. According to Lu et al. (2022), Seyedalmoosavi et al. (2022), and Shumo et al. (2019) protein content reflects the larvae's ability to utilize and convert feed nutrients into body tissue. The higher the protein content, the more efficient the metabolism and growth of BSF larvae in utilizing organic matter for energy and nutrition. In this study, protein content analysis was conducted at the UNDIP Integrated Laboratory using the Kjeldahl method to ensure the accuracy of the protein measurement results.

Result and Discussion

WRI Parameter

The research conducted obtained raw data from each treatment with different types of music as environmental stimuli for BSF larvae. The data were then processed to generate WRI values. After the WRI values were obtained, the data were entered into SPSS software for ANOVA testing. The data shown in Table 1 are normally distributed, allowing ANOVA to be used to determine their significance.

Table 1. WRI normal data

Music Genre	Shapiro-Wilk Statistic	df	Sig.
A	0.07	14	0.05
B	0.07	14	0.38
C	0.07	14	0.57
D	0.06	14	0.10
E	0.06	14	0.13

Note: df = degrees of freedom; Sig. = significance.

Based on the data presented in Table 2, the classical music treatment (D) showed the highest mean value among all treatments.

Next, an ANOVA test was conducted to determine whether there were significant differences in values between groups. Judging from the homogeneous data as

shown in the table below, the data is not homogeneous because all Sig. values < 0.05, which indicates that the variance between groups is not homogeneous (not the same) so that the Welch ANOVA test will be used.

Table 2. Mean of WRI

Music Genre	Mean
A	51.49
B	53.70
C	55.22
D	55.84
E	54.25

Table 3. Test of homogeneity of variances (WRI)

Test Method	Levene Statistic	df1	df2	Sig.
Based on Mean	06.07	4	65	0.00
Based on Median	0.26	4	65	0.00
Based on Median (adjusted df)	0.26	4	54.67	0.00
Based on Trimmed Mean	0.27	4	65	0.00

The test results below show a Welch ANOVA value of 0.106, greater than 0.05, which indicates there is no statistically significant difference in the average WRI score. Although descriptively the classical music group has the highest average, the Welch ANOVA results show no significant difference.

Table 4. ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	119.26	4	29.82	0.64	0.64
Within Groups	3041.27	65	46.79		
Total	3160.54	69			
Robust Test of Equality of Means:					
	Statistic[a]	df1	df2		Sig.
Welch	2.10	4	29.19		.106

Note: df = degrees of freedom; Sig. = significance.
a = asymptotically F-distributed.

The results showed that the highest Waste Reduction Index (WRI) value was descriptively observed in the classical music treatment compared to other treatments. However, statistically, there was no significant difference among treatments ($p > 0.05$).

ECD Parameter

Similar to processing WRI data, the research obtained raw data from each treatment with different types of music as environmental stimuli for BSF larvae. The data were then processed to generate ECD values. After the ECD values were obtained, the data were entered into SPSS software for ANOVA testing. The data shown in Table 5 are normally distributed, allowing ANOVA to be used to determine their significance.

Table 5. ECD normal data

Music Genre	Shapiro-Wilk Statistic	df	Sig.
A	0.95	14	0.55
B	0.95	14	0.54
C	0.95	14	0.41
D	0.93	14	0.34
E	0.92	14	0.20

Based on the data presented in Table 6, the classical music treatment (D) showed the highest mean value among all treatments.

Table 6. Mean of ECD

Music Genre	Mean
A	0.0441
B	0.0440
C	0.0426
D	0.0449
E	0.0448

Next, an ANOVA test was conducted to determine whether there were significant differences in values between groups. Based on the homogeneity test results (Levene's test) shown in the table below, the data were homogeneous because the significance value was greater than 0.05, indicating that the variance between groups was equal. Therefore, a one-way ANOVA test was used to analyze the differences among treatments.

Table 7. Test of homogeneity of variances (ECD)

Test Method	Levene Statistic	df1	df2	Sig.
Based on Mean	1.34	4	65	.27
Based on Median	.96	4	65	.44
Based on Median (adjusted df)	.96	4	55.21	.44
Based on Trimmed Mean	1.35	4	65	.26

The test results below show an ANOVA value of 0.20, greater than 0.05, which indicates there is no statistically significant difference in the average ECD score. Although descriptively the classical music (D) group has the highest average, the ANOVA results show no significant difference.

Table 8. ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.00	4	0.00	0.04	0.20
Within Groups	0.02	65	0.00		
Total	0.02	69			

Note: df = degrees of freedom; Sig. = significance.
a = asymptotically F-distributed.

The results showed that the highest Efficiency of Conversion of Digested Food (ECD) value was descriptively observed in the classical music treatment (D) compared to other treatments. However,

statistically, there was no significant difference among treatments ($p > 0.05$).

Survival Rate Parameter

From the research that has been carried out, raw data were obtained from each treatment with different types of music as environmental stimuli for BSF larvae, which were then processed and entered into Equation 3.

Table 9. SR value

Music Genre	SR (%)
A	98.5
B	93.5
C	95
D	98
E	97

SR differs from other parameters because it is based on the number of surviving larvae from the beginning to the end of the treatment, not on daily measurements. Therefore, SR data are presented descriptively to illustrate the percentage of larval survival in each treatment. The graph below shows that the group with the no-music treatment (A) had the highest SR value, at 98.5%, and the group with the random music treatment had the lowest, at 93.5%(B).

Protein Content Parameter

In this study, protein content analysis was carried out at the UNDIP Integrated Laboratory using the Kjeldahl method to ensure the accuracy of the protein measurement results.

Table 10. Protein content

Code	Parameter	Value/result (%)
A	Protein content	16.6
B	Protein content	16.31
C	Protein content	16.05
D	Protein content	15.9
E	Protein content	16

Similar to SR, protein levels have different characteristics than data for other parameters. Therefore, protein level data are presented only descriptively to illustrate the protein levels in each treatment. From the graph below, we can see that the group with the no music treatment (A) had the highest protein value of 16.6.

The Influence of Musical Variations

Based on the results of the study, four main parameters were obtained for each treatment, namely WRI, ECD, survival rate (SR), and protein content. Descriptively, the highest WRI and ECD values were observed in the classical music treatment, while the highest SR and protein content were found in the no-music treatment. This indicates that each treatment exhibited advantages in different parameters. However, based on statistical analysis, no significant differences were found among treatments ($p > 0.05$).

The relatively higher WRI and ECD values observed in the classical music treatment may be related to the characteristics of classical music, which typically has a more stable tempo and relatively lower intensity, potentially creating a calmer environmental condition for Black Soldier Fly (BSF) larvae. This is in line with Alworth & Buerkle (2013), who stated that musical stimuli with stable rhythms tend to provide a more conducive environment for animals compared to sounds with faster or irregular rhythms. Other studies have also reported that structured sound patterns can create more stable environmental conditions that support organisms at the larval stage (Ren et al., 2022). In addition, feed conversion efficiency in BSF larvae is influenced by environmental conditions that support feeding and metabolic activities (Lalander et al., 2020).

Meanwhile, the highest survival rate (SR) and protein content were observed in the no-music treatment. This suggests that BSF larvae may perform more stably under environmental conditions without additional sound stimuli. According to Stocks (2012), insects are generally more responsive to physical environmental factors such as temperature and feed availability than to auditory stimuli. Furthermore, the nutritional composition of BSF larvae is more strongly influenced by the quality and type of substrate rather than additional environmental factors (Diener et al., 2011).

Several previous studies have also reported that sound exposure does not always significantly affect organism performance, particularly during the larval stage. Lee et al. (2024) found that *Lymantria dispar* caterpillars did not show differences in response to different sound treatments. Similarly, You & Tinoco (2021) reported that fish larvae exhibited similar responses across various sound frequencies. In addition, Villalobos-Jiménez et al. (2017) found no significant differences between treatment and control groups.

The lack of significant effects of music variation in this study may be due to the biological characteristics of BSF larvae, which do not possess auditory systems like vertebrates. Instead, larvae primarily respond to vibrations generated by sound rather than the type of music itself. Since sound intensity was maintained at similar levels across treatments, the stimuli received by the larvae were relatively uniform. This is consistent with Hawkins & Popper (2017) and Hubert et al. (2020), who stated that when intensity and duration of sound exposure are not sufficiently differentiated, organisms tend to respond similarly to acoustic stimuli. Moreover,

many invertebrates detect sound through particle motion and substrate vibrations rather than sound pressure (Davies et al., 2024).

Therefore, although descriptively higher values were observed in the classical music treatment for certain parameters such as WRI and ECD, these differences were not statistically significant. This suggests that the effect of music variation on BSF larval performance is limited under the conditions of this study. This result may be influenced by environmental factors that potentially play a more dominant role than the treatment applied (Mappanganro et al., 2023). Previous studies have shown that the performance of BSF larvae in organic waste treatment is influenced by environmental conditions and substrate characteristics, which play a more dominant role than additional external factors (Irwanto et al., 2025). Other environmental factors, such as substrate composition, temperature, humidity, pH, feeding rate, and aeration, are likely to play a more dominant role in influencing larval performance. This is supported by previous studies, including, Abduh et al. (2022), Palma et al. (2018), Lalander et al. (2020), Fitriana et al. (2022), Arabzadeh et al. (2022), Khasanah et al. (2024), Chia et al. (2018), Shumo et al. (2019), Qomi et al. (2021), Ma et al. (2018), Meneguz et al. (2018), and Siddiqui et al. (2024), which highlight the importance of these factors in BSF based bioconversion processes.

Conclusion

This study aimed to analyze the effect of music variations on the bioconversion performance of organic waste using Black Soldier Fly (BSF) larvae. The results showed that there was no significant difference in Waste Reduction Index (WRI) and Efficiency of Conversion of Digested feed (ECD) based on ANOVA analysis. However, descriptively, classical music tended to show the highest values for both WRI and ECD compared to other treatments. Meanwhile, survival rate (SR) and protein content were analyzed descriptively, and the highest values were found in the non-music treatment. The use of music with an intensity of 60–80 dB for 6 hours per day gave a neutral effect on the bioconversion performance of BSF larvae under the tested conditions. Further research is suggested to explore different music intensity, frequency, and duration, and also to focus more on vibration based stimulation, so the potential effect on improving BSF larvae performance in organic waste treatment can be better understood.

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Author Contributions
Conceptualization, S.S.; methodology, supervision, B.S.R.; formal analysis, investigation, resources, data curation, writing original draft preparation, writing review and editing, visualization, project administration, funding acquisition, D.A.; Validation, S.S. and B.S.R. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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