



Analysis of Dry Leaf Compost Quality Using Mealworm (*Tenebrio molitor*) with EM4 Addition

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Article Info	Abstract
Article history: Received 2 October 2025 Revised 25 December 2025 Accepted 26 December 2025 Published 28 December 2025 Keywords: Compost quality, Dry leaf waste, EM4, Mealworm, <i>Tenebrio molitor</i>.	Background: Dry leaf waste is commonly discarded or burned, which may contribute to environmental pollution despite its potential for biological conversion into useful products. Bioconversion using mealworm (<i>Tenebrio molitor</i>) combined with EM4 offers an alternative approach for converting dry leaf waste into compost. Aims: This study aimed to analyze the quality of dry leaf compost produced using <i>T. molitor</i> with EM4 addition and to evaluate its conformity with SNI 19-7030-2004. Methods: This experimental study applied a bioconversion method for 25 days using four treatment reactors: dry leaves with EM4 and polar (R1), dry leaves with polar (R2), dry leaves with EM4 (R3), and dry leaves without EM4 or polar (R4). Mealworms were used as bioconversion agents, with 100 g of feed provided every five days. Compost quality was evaluated based on moisture content, pH, temperature, color, feed consumption, phosphorus, and C/N ratio. The results were descriptively evaluated against SNI 19-7030-2004. Result & Conclusion: Moisture content and temperature met the SNI requirements in all reactors, whereas phosphorus remained below the required minimum. Conformity with the pH, color, and C/N ratio requirements varied among treatments. R3 showed the closest overall conformity with the standard, meeting the requirements for moisture content, temperature, color, and C/N ratio, while meeting the pH requirement at most observation points. However, its phosphorus content remained below the required level. These findings indicate the potential of mealworm-assisted bioconversion with EM4 for dry leaf waste composting, although further optimization is required to improve nutrient quality.
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1. Introduction

Solid waste management remains a major environmental challenge in Indonesia. According to the National Waste Management Information System (SIPSN), only 24.73% of waste is currently classified as managed, while approximately 75% remains unmanaged (KLH/BPLH, 2026). This substantial proportion of unmanaged waste highlights the continuing need for alternative waste management approaches that promote waste reduction and resource recovery. Dry leaves represent one type of organic waste that is commonly disposed of at temporary disposal sites or burned, potentially contributing to environmental pollution (Muhayyat et al., 2016). Therefore,

utilizing dry leaves as a raw material for value-added products such as compost provides an alternative approach to reducing organic waste.

Dry leaves have potential as a raw material for compost production; however, their decomposition tends to be slow because plant residues contain lignocellulosic components, including cellulose, hemicellulose, and lignin, which are relatively resistant to degradation (He *et al.*, 2021; Gao *et al.*, 2025). Lignocellulose is therefore an important factor influencing the decomposition process and compost quality, while its breakdown is strongly associated with microbial and enzymatic activities during composting (Meng *et al.*, 2022; Gao *et al.*, 2025). Insect-based bioconversion provides an alternative strategy for converting organic residues into useful products. Among potential bioconversion agents, the yellow mealworm (*Tenebrio molitor*) is capable of utilizing various lignocellulosic substrates, including agricultural residues and cellulose-rich materials (He *et al.*, 2021; Mao *et al.*, 2024). The utilization of these substrates is also associated with the gut microbiota of *T. molitor*, including microorganisms involved in the degradation of complex plant materials (Mamtimin *et al.*, 2023; Mao *et al.*, 2024). These characteristics provide a scientific basis for investigating *T. molitor* as a bioconversion agent for dry leaf waste.

The decomposition of dry leaves may also be supported by microbial activators. Effective Microorganisms-4 (EM4) has been applied as a bioactivator in composting to facilitate the decomposition and fermentation of organic materials. The application of effective microorganisms in composting systems containing dried leaves has been associated with changes in early composting temperature, odor suppression, humification, and other indicators of organic matter decomposition (Fan *et al.*, 2018). More recent studies have also investigated EM4-based treatments for dry leaf composting and reported their potential to support biodegradation and improve several compost quality characteristics (Damayanti *et al.*, 2026; Fachriah *et al.*, 2026). The combination of *T. molitor* as a bioconversion agent and EM4 as a microbial activator may therefore provide an alternative biological approach for converting dry leaf waste into compost.

Previous studies have separately investigated insect-based bioconversion for organic waste management, the utilization of lignocellulosic residues by *T. molitor* (He *et al.*, 2021; Mao *et al.*, 2024), and the application of microbial activators in the composting of plant-derived residues (Fan *et al.*, 2018; Damayanti *et al.*, 2026). However, evidence specifically evaluating the quality of compost produced from dry leaves through *T. molitor*-assisted bioconversion combined with EM4 remains limited. In particular, evaluation of both physical characteristics and nutrient composition is required to determine whether the resulting compost conforms to established compost quality standards. Therefore, this study aimed to analyze the quality of compost produced from dry leaf waste using *T. molitor* with EM4 addition and to evaluate its conformity with SNI 19-7030-2004 based on moisture content, pH, temperature, color, phosphorus, and C/N ratio.

2. Material and Method

2.1 Experimental Design and Treatment

This experimental study was conducted from March to August 2022 at the Environmental Engineering Workshop and Environmental Quality Laboratory, Universitas Islam Indonesia, Yogyakarta. Dry leaves were used as the main substrate, while yellow mealworm (*Tenebrio molitor*) larvae were used as the bioconversion agent. Effective Microorganisms-4 (EM4) was applied as a microbial treatment to the dry leaves prior to bioconversion.

The composting experiment was conducted for 25 days using four plastic reactors measuring 47 × 34 × 15 cm. Each reactor contained an initial mealworm weight of 100 g and received 100 g of feed every five days. Four feed treatments were applied: R1 consisted of 50 g of EM4-treated dry leaves and 50 g of polar; R2 consisted of 50 g of untreated dry leaves and 50 g of polar; R3 consisted of 100 g of EM4-treated dry leaves; and R4 consisted of 100 g of untreated dry leaves. The experimental treatments are summarized in Table 1.

Table 1. Experimental treatments and feed composition

Reactor	Treatment	EM4-treated dry leaves (g)	Untreated dry leaves (g)	Polar (g)	Total feed (g)
R1	EM4-treated dry leaves + polar	50	–	50	100
R2	Untreated dry leaves + polar	–	50	50	100
R3	EM4-treated dry leaves	100	–	–	100
R4	Untreated dry leaves	–	100	–	100

2.2 Composting and Bioconversion Process

The composting process was carried out using four treatment reactors, with *T. molitor* larvae used as the bioconversion agent to decompose the dry leaf substrate. The experimental setup of the four composting reactors used during the bioconversion process is shown in Figure 1.

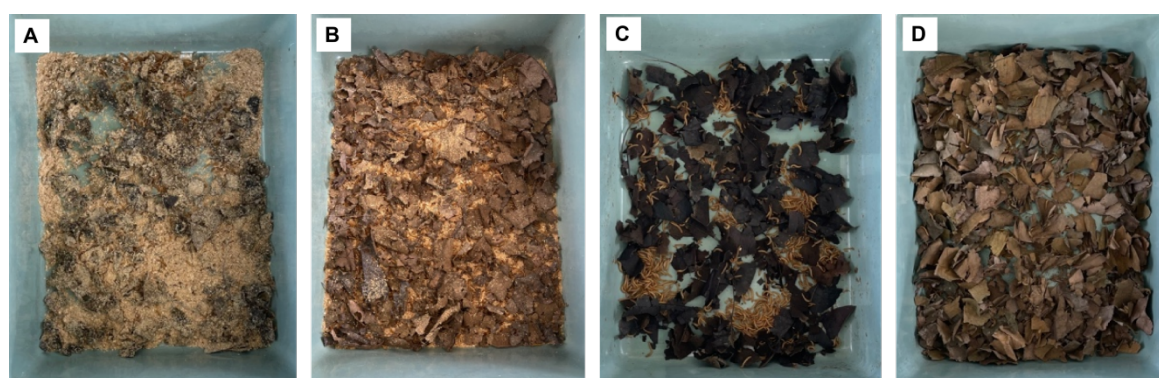


Figure 1. Composting reactors used in the experiment: (a) R1, EM4-treated dry leaves + polar; (b) R2, untreated dry leaves + polar; (c) R3, EM4-treated dry leaves; and (d) R4, untreated dry leaves.

For treatments involving EM4 (R1 and R3), the dry leaves were treated with EM4 before being provided to the mealworms. Feed was supplied to each reactor at 100 g every five days according to the treatment composition presented in Table 1. The bioconversion process was conducted for 25 days, during which the physical characteristics of the compost and feed consumption were monitored periodically.

2.3 Physical Characteristics and Feed Consumption

The physical characteristics evaluated included moisture content, pH, temperature, and color. Measurements were conducted on days 5, 10, 15, 20, and 25 of the bioconversion process. Moisture content was determined using the gravimetric method, pH was measured using a pH meter, and temperature was measured using a thermometer. Color changes were observed periodically during the composting process.

Feed consumption by *T. molitor* was also monitored during the bioconversion process to evaluate the utilization of the feed substrate in each treatment. The observed physical characteristics of the resulting compost were subsequently compared with the requirements specified in SNI 19-7030-2004 for compost derived from domestic organic waste.

2.4 Nutrient Analysis

The nutrient characteristics evaluated included nitrogen (N), organic carbon (C), phosphorus (P), potassium (K), and the C/N ratio. Nitrogen content was determined using the Kjeldahl method on day 25, whereas organic carbon was analyzed using the Walkley–Black method on days 5 and 25. Phosphorus and potassium were analyzed on days 5 and 25 following acid digestion using HNO_3 and HClO_4 . The chemical analyses followed the procedures described in the *Technical Guidelines for Chemical Analysis of Soil, Plants, Water, and Fertilizers* (Sulaeman et al., 2005). The

C/N ratio was determined from the measured organic carbon and nitrogen contents. The nutrient characteristics of the compost were evaluated against the minimum or recommended values specified in SNI 19-7030-2004.

2.5 Data Analysis

The experimental data were analyzed descriptively to evaluate changes in compost characteristics during the 25-day bioconversion process and to compare the responses among the four treatment reactors. Results for moisture content, pH, temperature, color, phosphorus, potassium, and C/N ratio were evaluated for conformity with SNI 19-7030-2004. Feed consumption was descriptively evaluated to characterize substrate utilization by *T. molitor* during the bioconversion process.

3. Results and Discussion

3.1 Physical Characteristics of Compost

The physical characteristics of the compost were evaluated based on moisture content, pH, temperature, and color during the 25-day bioconversion process. These parameters were monitored periodically to assess changes in the composting material and its conformity with SNI 19-7030-2004.

3.1.1 Moisture Content

Moisture content fluctuated during the 25-day bioconversion process in all treatments, as shown in Figure 2. The observed values ranged from 11.69% to 17.67%, with the highest moisture content recorded in R1 and the lowest in R4. Despite the fluctuations among treatments, all moisture values remained below the maximum limit of 50% specified in SNI 19-7030-2004.

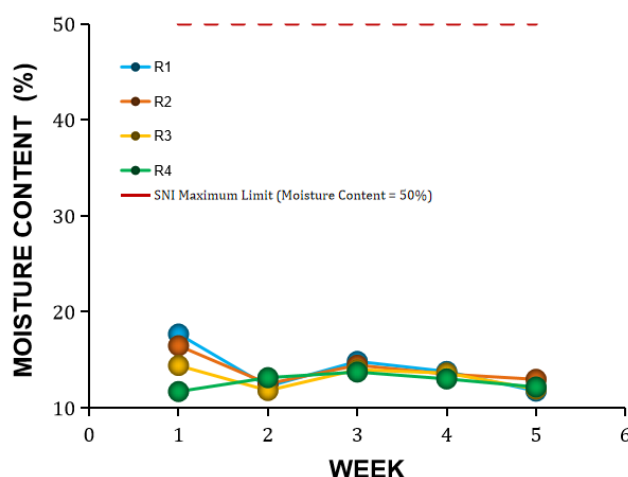


Figure 2. Changes in compost moisture content during the 25-day bioconversion process.

The relatively low moisture content indicates that the composting material did not accumulate excessive water during the process. Moisture is an important factor in organic matter decomposition because water availability affects biological activity within the substrate (Sun *et al.*, 2024). However, the moisture contents obtained in this study were considerably lower than those reported by Rolita *et al.* (2017), moisture contents of 56.44–80% in composting dry leaf waste using mealworms. Differences in substrate composition and treatment conditions may contribute to differences in moisture characteristics between composting systems (Sun *et al.*, 2024; Wang *et al.*, 2024).

3.1.2 pH

The pH of the compost also fluctuated during the observation period (Figure 3), ranging from approximately 6.15 to 7.86. SNI 19-7030-2004 specifies a pH range of 6.80–7.49. R1, R2, and R4 showed values outside this range at several observation points, whereas R3 met the requirement on days 5, 15, 20, and 25 but not on day 10.

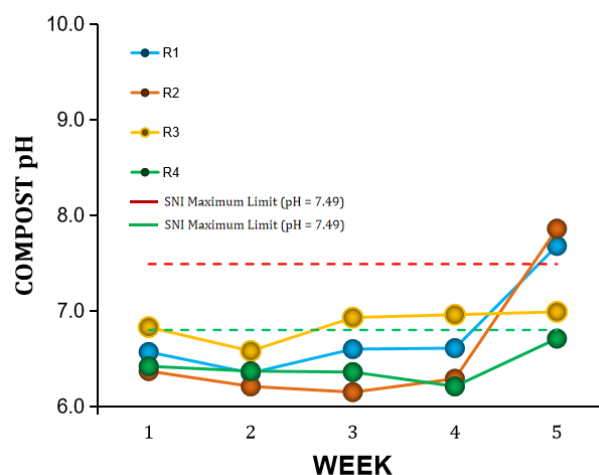


Figure 3. Changes in compost pH during the 25-day bioconversion process.

Changes in pH during decomposition can occur as organic compounds are transformed through microbial and biological activity (Sun *et al.*, 2024; Verardi *et al.*, 2025). The pH values obtained in this study were generally within or close to the range previously reported for mealworm-assisted composting (Iresha *et al.*, 2023; Boonthong *et al.*, 2025). Raraningsih *et al.* (2017), for example, reported compost pH values ranging from 6.95 to 8.47 in a composting system involving mealworm-related bioconversion. Among the treatments in the present study, R3 showed the most consistent conformity with the SNI pH requirement. The use of EM4-treated dry leaves in this treatment may have contributed to the biological transformation of the substrate; however, the present descriptive data do not allow the contribution of EM4 to be separated from other treatment-related factors (Iresha *et al.*, 2023).

3.1.3 Temperature

Changes in compost temperature during the bioconversion process are presented in Figure 4. The recorded compost temperatures ranged from approximately 24.4 to 26°C and showed relatively small fluctuations throughout the observation period.

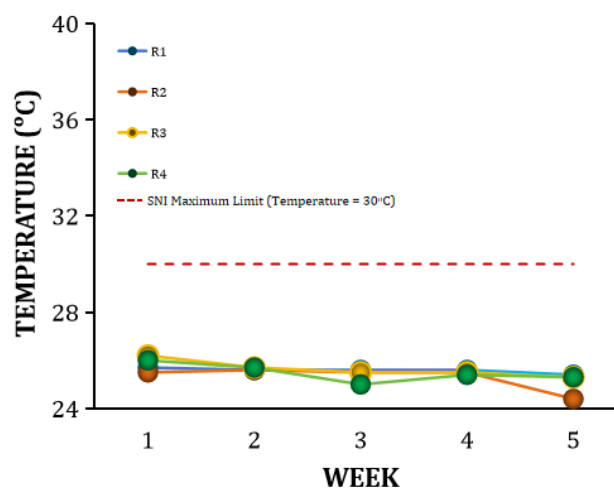


Figure 4. Changes in compost temperature during the 25-day bioconversion process.

The recorded temperatures met the temperature criterion used in SNI 19-7030-2004. The relatively moderate temperature profile indicates that the small-scale mealworm-assisted system did not exhibit a pronounced thermophilic phase (Iresha *et al.*, 2023; Saypariya *et al.*, 2024). This differs from conventional composting systems, in which intensive microbial decomposition may produce substantial heat (Sun *et al.*, 2024; Du *et al.*, 2026). Recent evaluations of composting processes also emphasize that temperature development depends strongly on substrate

properties, microbial activity, aeration, moisture, and the configuration and scale of the composting system (Saypariya *et al.*, 2024; Wang *et al.*, 2024; Du *et al.*, 2026).

The present system combined biological conversion by *T. molitor* with microbial decomposition. Previous research has demonstrated that *T. molitor* can consume lignocellulosic residues and contribute to the degradation of cellulose, hemicellulose, and lignin, while the resulting frass can subsequently be converted into fertilizer material (Yang *et al.*, 2019; He *et al.*, 2021; Mao *et al.*, 2024). Therefore, the temperature profile observed in the present experiment should be interpreted within the context of a mealworm-assisted bioconversion system rather than conventional thermophilic composting alone.

3.1.4 Color

Color changes provided an additional physical indication of the transformation of the dry leaf substrate. The observed compost colors during the 25-day bioconversion period are presented in Table 2.

Table 2. Compost color during the 25-day bioconversion process

Treatment	Day 5	Day 10	Day 15	Day 20	Day 25
R1	Brown	Brown	Brown	Brown	Brown
R2	Brown	Brown	Brown	Brown	Brown
R3	Dark brown	Dark brown	Dark brown	Dark brown	Dark brown
R4	Dark brown	Dark brown	Dark brown	Dark brown	Dark brown

R1 and R2 remained brown throughout the observation period, whereas R3 and R4 exhibited a dark-brown appearance. Based on the color criterion in SNI 19-7030-2004, R3 and R4 showed conformity with the expected dark coloration of mature compost, while R1 and R2 did not. The difference between these groups also coincided with substrate composition: R1 and R2 contained polar, whereas R3 and R4 contained only dry leaves as the feed substrate. Nevertheless, because these treatment factors were not independently evaluated statistically, the observed color differences cannot be attributed solely to the presence or absence of polar.

Overall, the physical characteristics showed different levels of conformity among the treatments. Moisture content and temperature met the evaluated SNI requirements in all reactors, while conformity of pH and color varied. R3 showed the most consistent physical characteristics, meeting the moisture, temperature, and color requirements and remaining within the required pH range at most observation points.

3.2 Mealworm Growth and Substrate Utilization

Changes in mealworm weight, compost weight, and feed consumption were monitored during the bioconversion process to describe the interaction between *T. molitor* and the supplied substrates. The changes in mealworm weight during the experimental period are shown in Figure 5.

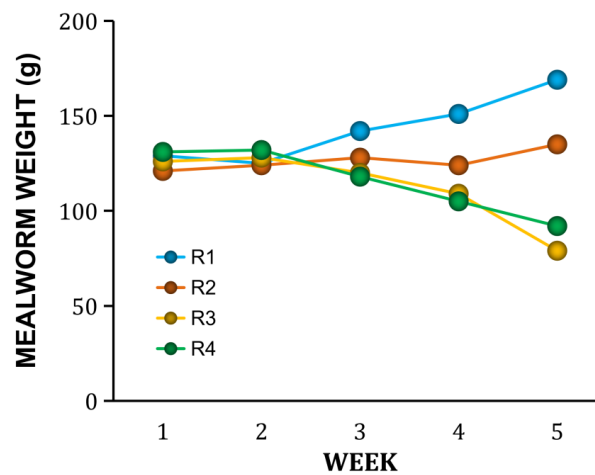


Figure 5. Changes in mealworm weight during the bioconversion process.

Mealworm weight varied among treatments and throughout the observation period, indicating different responses to the supplied feed substrates. Substrate composition is an important factor in mealworm growth and utilization (Harsányi *et al.*, 2020; Montalbán *et al.*, 2023; Liu *et al.*, 2026). Recent studies have shown that *T. molitor* can utilize lignocellulosic materials, although the nutritional composition of the substrate influences conversion, and larval performance (He *et al.*, 2021; Montalbán *et al.*, 2023; Mao *et al.*, 2024). Lignocellulose-based diets may also provide less favorable conditions for mealworm development than nutritionally richer diets, indicating that substrate utilization does not necessarily correspond directly to optimal larval growth (Harsányi *et al.*, 2020; Montalbán *et al.*, 2023). Changes in the weight of the resulting compost material are presented in Figure 6.

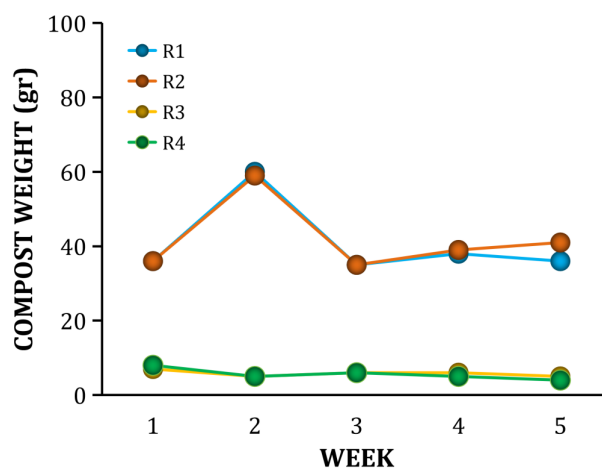


Figure 6. Changes in compost weight during the bioconversion process.

Changes in compost weight reflect the transformation and utilization of the supplied organic material during bioconversion. *T. molitor* is capable of ingesting lignocellulosic residues, while part of the consumed material is converted into larval biomass, metabolic products, and frass (Iresha *et al.*, 2023; He *et al.*, 2021). He *et al.* (2021) similarly demonstrated the utilization and biodegradation of lignocellulosic crop residues by *T. molitor*, supporting the potential application of mealworms in biological processing of plant-derived residues. Feed consumption also fluctuated during the experimental period, as shown in Figure 7.

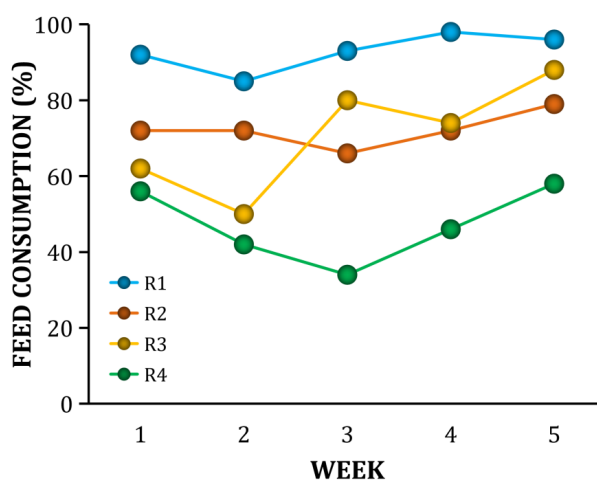


Figure 7. Feed consumption by *T. molitor* during the 25-day bioconversion process.

Feed was consumed in all four treatments, demonstrating that *T. molitor* was able to utilize the supplied dry leaf-based substrates (Iresha *et al.*, 2023; He *et al.*, 2021; Montalbán *et al.*, 2023).

However, the consumption pattern was not constant during the observation period. Differences among treatments may be related to the composition and nutritional characteristics of the feed (Harsányi *et al.*, 2020; Liu *et al.*, 2026). Studies on lignocellulosic residues have shown that mealworm consumption and conversion can be enhanced when lignocellulosic substrates are combined with additional nutritional sources (Iresha *et al.*, 2023; He *et al.*, 2021; Montalbán *et al.*, 2023). This is relevant to the present experiment because R1 and R2 contained polar in addition to dry leaves, whereas R3 and R4 contained dry leaves without polar.

The observed patterns should nevertheless be interpreted descriptively because the available experimental design does not support statistical inference regarding treatment effects. Therefore, the results demonstrate substrate utilization by *T. molitor* but do not establish that one treatment caused significantly greater consumption or larval growth than another.

3.3 Nutrient Characteristics of Compost

The nutrient characteristics evaluated in the resulting compost included phosphorus (P), potassium (K), organic carbon (C), nitrogen (N), and the C/N ratio. These parameters provide complementary information on nutrient composition and the transformation of organic material during bioconversion.

3.3.1 Phosphorus

Phosphorus content on days 5 and 25 is shown in Figure 8. Phosphorus increased from 0.00014% to 0.00034% in R1, from 0.00012% to 0.00035% in R2, from 0.00007% to 0.00012% in R3, and from 0.00006% to 0.00033% in R4.

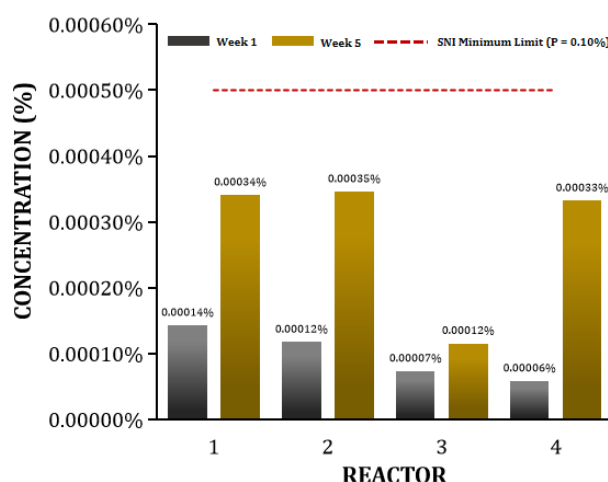


Figure 8. Phosphorus content of compost on days 5 and 25.

Although phosphorus increased in all treatments, the final values remained below the minimum requirement of 0.10% specified in SNI 19-7030-2004. This indicates that the dry leaf-based substrates did not provide sufficient phosphorus for the resulting compost to meet the standard within the 25-day bioconversion period. Nutrient characteristics of insect-derived organic fertilizer are strongly influenced by the composition of the material consumed by the insects (Zunzunegui *et al.*, 2024; Kryeziu *et al.*, 2026). Recent studies of *T. molitor* frass have similarly shown that its fertilizer properties and nutrient supply depend on the feeding substrate and resulting nutrient composition (Beesigamukama *et al.*, 2022; Kryeziu *et al.*, 2026).

3.3.2 Organic Carbon, Nitrogen, and C/N Ratio

Organic carbon content changed between the initial and final observations, indicating transformation of carbon-containing organic matter during the bioconversion process. The changes in organic carbon among the four treatments are presented in Figure 9.

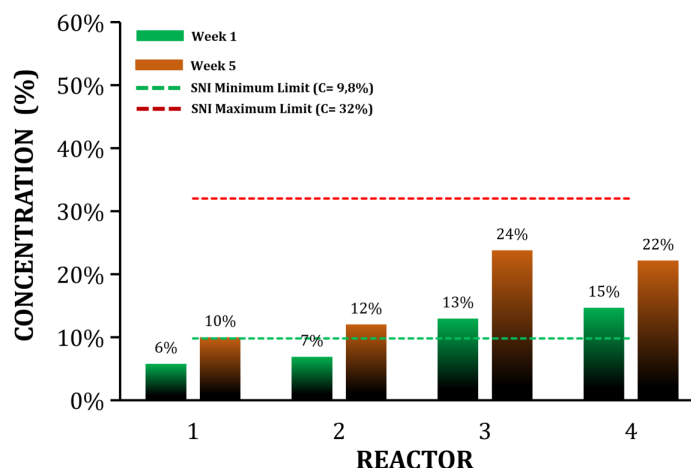


Figure 9. Organic carbon content of compost during the bioconversion process.

The changes in organic carbon may be associated with the degradation of organic matter during bioconversion. Dry leaves contain lignocellulosic components that are relatively resistant to degradation; however, *T. molitor* is capable of utilizing lignocellulosic substrates and contributing to the degradation of cellulose, hemicellulose, and lignin (Houben *et al.*, 2020; He *et al.*, 2021; Mao *et al.*, 2024).

Nitrogen content was determined at the end of the bioconversion process to evaluate the nitrogen characteristics of the resulting compost. Differences in nitrogen content among R1–R4 are presented in Figure 10.

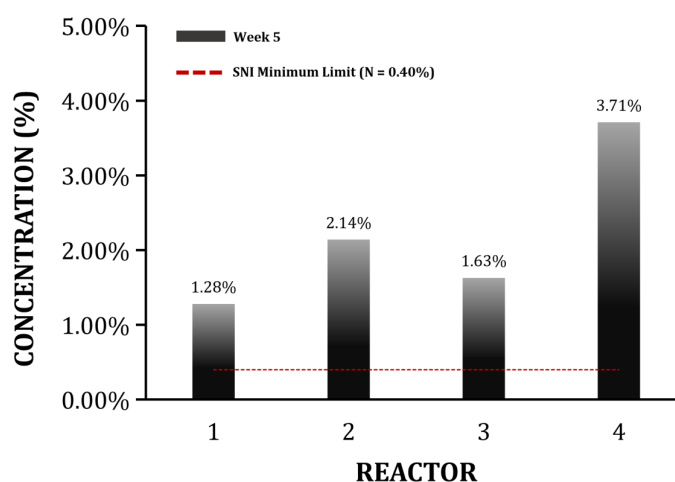


Figure 10. Nitrogen content of compost at the end of the bioconversion process.

The relationship between organic carbon and nitrogen was further evaluated through the C/N ratio. The final C/N ratios were 7.81, 5.61, 14.59, and 5.97 for R1, R2, R3, and R4, respectively, as presented in Figure 11.

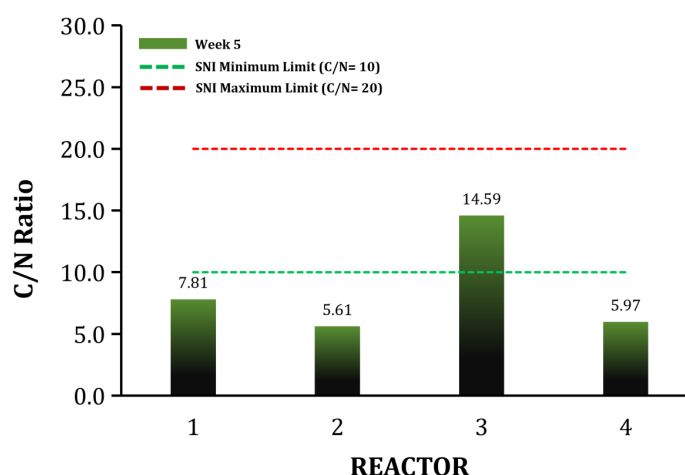


Figure 11. C/N ratio of compost at the end of the bioconversion process.

Based on the SNI 19-7030-2004 requirement of 10–20, only R3 met the C/N ratio standard. Differences in nutrient characteristics among treatments may be associated with differences in substrate composition and subsequent biological transformation, as the nutrient characteristics of mealworm-derived organic residues are influenced by the feeding substrate (Beesigamukama *et al.*, 2022; Verardi *et al.*, 2025; Kryeziu *et al.*, 2026).

Overall, none of the treatments met all evaluated requirements of SNI 19-7030-2004. R3 showed the closest overall conformity, meeting the requirements for moisture, temperature, color, potassium, and C/N ratio, as well as the pH requirement at most observation points, although its phosphorus content remained below the required minimum.

4. Conclusion

The study found that mealworm-assisted bioconversion produced compost with different physical and nutrient characteristics among the four treatments. Moisture content ranged from 11.69% to 17.67% and compost temperature from approximately 24.4 to 26°C, both meeting the requirements of SNI 19-7030-2004. Phosphorus content remained below the minimum requirement of 0.10% in all treatments. The final C/N ratios were 7.81, 5.61, 14.59, and 5.97 for R1, R2, R3, and R4, respectively, with only R3 meeting the required range of 10–20. Overall, R3, consisting of EM4-treated dry leaves, showed the closest conformity with the evaluated compost quality requirements.

The results indicate that *Tenebrio molitor*-assisted bioconversion has potential for converting dry leaf waste into compost. Further optimization of substrate composition and the bioconversion process is required to improve nutrient quality, particularly phosphorus content, and achieve more consistent conformity with compost quality standards.

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