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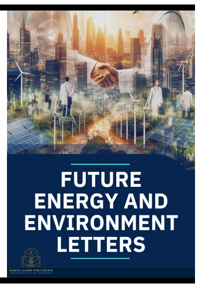

Biocomposting of Organic Waste using Vertical Reactor and Active Aeration

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ABSTRACT

Industrial development and economic growth in this country have led to a significant increase in solid waste, driven by both population growth and higher consumption of resources. Food waste constitutes about 45% of daily solid waste, exacerbating the strain on existing landfills. To mitigate these challenges, composting food waste offers a solution by reducing landfill volume, promoting the use of organic fertilizers, and improving soil quality. In this study, 3 types of composting treatments were carried out, namely Treatment 1 (T1); organic waste and sawdust, Treatment 2 (T2); organic waste, sawdust and active aeration, Treatment 3 (T3); organic waste and active aeration and one Control Treatment (C); organic waste only. All treatment were conducted for 30 days using a vertical reactor. During the composting period, physical, chemical, and biological factors, including color, texture, odor, temperature, pH, moisture content, and microbial population were monitored to compare the compost produced by the different treatments. The results showed that the highest temperature recorded was 47.50°C in Treatment T2, while pH values ranged from 6.62 to 7.25. The average moisture content in each treatment ranged from 54.40% to 73.93%, with microbial populations peaking in the first week of composting. Based on this study, the T2 treatment produced the best compost yield based on the high GI value of green beans and mustard seeds. Therefore, T2 compost can be applied as a soil conditioner and organic fertilizer to create better soil conditions for plant growth.

1. Introduction

Municipal solid waste demands urgent attention and prioritized action from authorities, as it has been identified by the World Bank as one of the three primary contributors to environmental degradation in Asian countries [1]. In 2021, it was projected that by 2022, 14 million tons of waste would be collected annually. This upward trend is expected to persist, driven by a population growth rate of 1.8%. Waste collection data from 2012-2022 indicates that approximately 39,936 tons of waste were collected daily across Malaysia in 2022. Out of this, 45% of the total daily solid waste is food waste, with 4,046 tons, or 24%, being avoidable through proper management for sustainable waste practices [2]. Composting is one approach to addressing the growing issue of solid waste accumulation. It involves the decomposition of organic waste through the action of microorganisms

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such as bacteria, fungi, and earthworms, transforming it into a nutrient-rich soil amendment known as compost. This process is both environmentally sustainable and beneficial for waste management and soil improvement. Composting offers several advantages, including reducing the volume of waste sent to landfills, conserving valuable landfill space, and reducing harmful greenhouse gas emissions. Instead, waste is converted into a useful product that can enhance soil quality and promote plant growth [3]. Additionally, composting helps reduce the reliance on chemical fertilizers and pesticides by providing essential nutrients and fostering healthy soil microbiology, ultimately improving crop yields and minimizing the environmental impact of agriculture.

Effective composting involves the breakdown of organic waste in the presence of oxygen, moisture, and microorganisms. Materials are typically shredded to accelerate decomposition and then mixed in appropriate proportions to create an optimal environment for microbial activity. Various composting methods can be employed, such as aerobic composting, anaerobic composting, vermicomposting, and thermophilic composting. The choice of method depends on factors such as the type and amount of waste, the desired end product, and available resources. Aerobic composting is considered a cost-effective and simple technology for food waste management, making it suitable for home, school, or university settings [4]. However, the stability and maturity of the compost are crucial factors [5]. The rate of aeration is a key factor influencing the success of the composting process [6]. Inadequate aeration leads to anaerobic conditions due to insufficient oxygen, while excessive aeration can increase costs and slow down the composting process by causing the loss of heat, moisture, and ammonia. The optimal aeration rate depends on factors such as the composition of raw materials, the type of aeration employed [7] and the oxygen demand of microorganisms [8]. A study by Guo *et al*., [9] highlighted the importance of aeration rate in determining compost stability.

However, there are limited studies exist on the optimal aeration rates for maximizing compost stability and maturity in vertical reactor systems. Moreover, little is known about how these systems compare to other composting methods in terms of efficiency, environmental sustainability, and economic scalability. Additionally, current compost quality evaluations predominantly rely on seed germination indices, leaving other important indicators like microbial diversity and potential contaminants underexplored. Therefore, this study aims to compare composting processes for food waste using active aeration versus no aeration. The composting system employed in this study will use a vertical reactor, with physical and chemical properties monitored throughout the composting period. Finally, compost quality will be evaluated using seed germination indices, helping to assess the effectiveness of active aeration in the composting process.

2. Methodology

2.1 Experimental Design

The research methodology for composting organic waste consists of four main components which are sampling, laboratory analysis, composting treatment, and final compost quality assessment. The vertical reactor with dimension of 30 cm x 30 cmx 50 cm (length x width x height) has two main components namely (1) 4 tubing running parallel for aeration and (2) the pump (Model RESUN LP100 Low Noise Air Pump) to supply oxygen continuously to the system. An input for feeding aeration to the system is supplied with four silicone tubing’s at the side of the vertical reactor that connected to air pump. The air pump comes with outlet diameter 20 mm which suitable for larger aerobic treatment systems (ATS). Figure 1 showed a clearer illustration of the active aeration composting reactor used in this study.

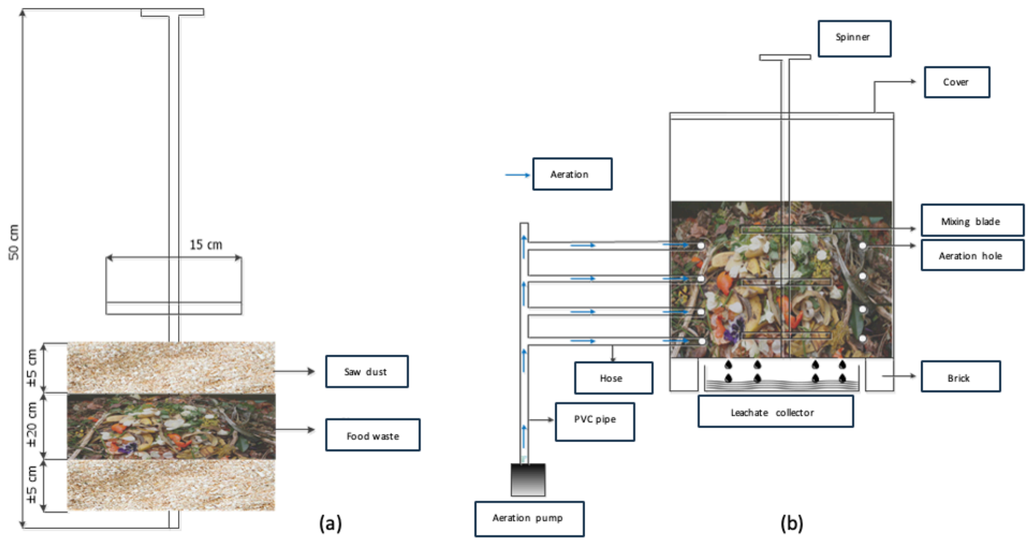


Fig. 1. (a) A compost reactor consist of (a) A mixing blades and arrangement of food waste and sawdust in the reactor (b) Compost reactor with aeration connection

2.2 Composting Process

The food waste was pre-shredded to an average particle size ranging from 1 to 3 cm. A bulking agent, specifically sawdust, was then added to each reactor at a ratio of 4:1 (food waste to sawdust by weight), with each ratio corresponding to 2 kg of material. Four composting reactors (40 cm × 38.5 cm) were constructed for the composting process. The experimental treatments was conducted as follows.

Table 1
Composting treatments applied in this study

No.	Treatments	Remarks
1.	Control (C)	Food waste only
2.	Reactor 1 (T1)	Food waste + sawdust
3.	Reactor 2 (T2)	Food waste + sawdust + aeration
4.	Reactor 3 (T3)	Food waste + aeration

2.3 Composting Process Monitoring

The composting material was turned once daily for 30 days treatment using the stirring handle located on the reactor lid. This turning process is crucial for ensuring adequate aeration, which helps to evenly distribute heat throughout the compost pile. The composting materials were mixed within the reactor to enhances the composting process by promoting microbial activity and facilitating the release of gases, as highlighted by Guo et al., [9]. The temperature and pH was measured daily for 1 minute in each compost reactor using a portable digital, at a depth of 15 cm at different points within the reactor. For moisture content the percentage was calculated using equation (1). The fresh sample was used for enumeration of microbial population by using serial dilution technique and calculated using equation (2). For germination index (GI), mung beans and mustard seeds was tested using a compost solution to determine the maturity level of the compost. The following equations (3) were used to calculate the relative seed germination percentage (RSG), relative root growth (RRG), and germination index (GI), as proposed by Zahrim *et al.*, [10].

$$\text{Moisture content (\%)} = \frac{(W2-W1)-(W3-W1)}{(W2-W1)} \times 100 \quad (1)$$

$$\text{Microbial population (CFU/mL)} = \frac{\text{Total colony} \times \text{dilution factor}}{\text{Inoculumn factor}} \quad (2)$$

$$\text{RSG (\%)} = \frac{\text{seed germination in sample}}{\text{seed germination in control}} \times 100 \quad (3)$$

$$\text{RRG (\%)} = \frac{\text{root length in sample}}{\text{root length in control}} \times 100$$

$$\text{GI (\%)} = \frac{\text{RSG} \times \text{RRG}}{100}$$

2.4 Statistical Analysis

The mean values and standard deviations were calculated using Microsoft Excel. The standard error was computed, and error bars were generated for the data. One-way ANOVA was performed to determine the p-value for comparisons between the composting treatment types and the seed germination index test.

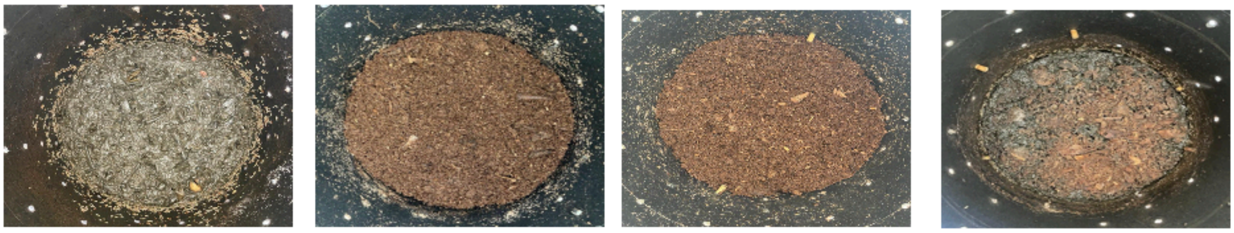
3. Results and Discussion

3.1 Physical Changes in Compost throughout the Composting Process

The physicochemical properties of the compost generated over the 30-day composting period were recorded. The data obtained on the physical changes in the compost—including color, odor, texture, and weight reduction—were analyzed for the different treatments: Control (food waste only), T1 (food waste and sawdust), T2 (food waste, sawdust, and active aeration), and T3 (food waste and active aeration). These changes will be discussed in detail in sections 3.1.1 to 3.1.2.

3.1.1 Color

Physical observations from this study indicate that all treatment samples exhibited a yellowish color during the first week of the composting process. By the fourth week, compost mixed with sawdust changed to a dark brown color (Figure 2 (b) and (c)), while compost without sawdust turned black (Figure 2 (a) and (d)). The stability of compost can be assessed by observing color changes during the composting process [11]. These color changes occur due to the decomposition of compost materials by microbes, which are linked to pH alterations. As microbes degrade these materials, the color shifts to dark brown or black due to the formation of humic substances, which are complex organic molecules rich in carbon and nitrogen [12]. According to Mbuligwe *et al.*, [11], color changes during composting reflect both the aesthetic quality and the characteristics of the final compost, indicating its stability. The results indicate that after 30 days of composting, the compost had turned dark, which serves as an indicator of compost stability. The color changes during composting are attributed to the presence of dissolved organic materials and particles. Dark-colored compost tends to have high light absorption and low light reflectance (known as albedo). As a result, dark compost heats up more quickly due to its high light absorption compared to lighter-colored compost [13].



(a) (b) (c) (d)

Fig. 2. The color changes in compost after 30 days of composting period (a) Control treatment (b) Treatment 1 (c) Treatment 2 and (d) Treatment 3

3.1.2 Compost texture and odor

The particle size of compost is related to its maturity level and the volume of material. As the compost matures, the fiber content decreases, and the particle size becomes smaller [14]. Consequently, the weight of the compost also decreases. An effective composting process results in a uniform texture that is easily disintegrated [14]. Based on the observations from this study, it was found that the compost texture on the final day of composting in treatments T1 and T2 was light, porous, moist, easily disintegrated, and uniform, which promoted good airflow, similar to the texture of sawdust used in these treatments [15]. In contrast, the compost texture in the Control (C) and T3 treatments was wet, compact, and heavy. This was due to the absence of sawdust in these treatments. Ultimately, the compost from treatments T1 and T2 can be categorized as mature and stable, making it suitable for use as organic fertilizer [14]. For compost odor, ammonia is a primary compound actively released from compost reactors [16], whereas no ammonia is emitted from mature compost. In this study, treatments T1 and T2 did not produce foul odors at the end of the composting process, while treatments C and T3 emitted a strong, unpleasant odor. The presence of foul and unpleasant odors typically indicates anaerobic conditions within the compost pile [17]. This is because, during the decomposition process, ammonia gas is generated. The oxidation reactions involved produce water and heat, which can result in the development of foul odors in the compost [14]. Meanwhile, the presence of an earthy smell in T1 and T2 suggests that the resulting compost has stabilized and matured [17]. Similar findings were reported by Md Sabiani and Asaari [17] and Petrick *et al*., [18], who also observed an earthy odor and the absence of foul smells in their compost samples. Changes in odor characteristics during the composting process are useful indicators of compost maturity and stability [14,17].

3.2 Chemical and Biological Factors Affecting the Composting Process

The composting process is influenced by several chemical and biological factors, including temperature, pH, moisture content, and microbial population. Data obtained from monitoring over the 30-day composting period were recorded and will be discussed in more detail in sections 3.2.1-3.2.4.

3.2.1 Temperature

Figure 3 illustrates the temperature changes in each of the different composting treatments. Temperature variation during composting in this study occurred through four degradation phases: mesophilic, thermophilic, cooling, and maturation. The temperature increased rapidly in treatments

T1 and T2, reaching a maximum on day 4, with average temperatures of 44.83°C and 47.50°C, respectively. Treatment C reached its maximum average temperature on day 8, at 35.67°C, while treatment T3 peaked on day 10, at 37.00°C. At the beginning of decomposition process, the temperature range on the first day for each treatment was between 22.17°C and 24.17°C, which is categorized as the mesophilic phase. This temperature range allows mesophilic microorganisms, such as bacteria and fungi, to decompose lignin and cellulose present in the compost pile. During this phase, mesophilic microbes use oxygen and easily degradable compounds, causing the temperature of the compost pile to rise rapidly [19]. From day 2 to day 4, treatments T1 and T2 exhibited drastic temperature changes, reaching the thermophilic phase. Thermophilic microorganisms are active during this phase, and the rapid decomposition of organic material leads to a significant rise in compost temperature as microbes utilize oxygen to break down organic matter into carbon dioxide, water vapor, and heat [19]. In contrast, treatment C entered the thermophilic phase between days 7 and 8, while treatment T3 entered this phase between days 8 and 10. This delay was due to the imbalance in the carbon-to-nitrogen ratio in these treatments, which caused the compost to take longer to degrade [20]. As a result, the temperature increase was slower in these treatments during composting, thereby slowing the degradation of organic material and nitrogen release [21]. In conclusion, during the initial decomposition phase, the mesophilic phase occurred with temperatures recorded between 22.17°C and 24.17°C, while the thermophilic phase temperatures ranged from 43.67°C to 47.50°C. In the maturation phase, the average temperature range recorded for treatments C, T1, T2, and T3 was between 30.17°C and 36.83°C. During this phase, the rate of decomposition decreases as the organic material in the compost pile stabilizes, resulting in lower temperatures and reduced microbial activity [22]. After day 5, treatments T1 and T2 began to show a temperature decline, while for treatments C and T3, the temperature decrease occurred on days 11. After days 5 and 11, the temperature in all treatments continued to decrease until it reached ambient temperature (30 ± 3°C) on the final day of composting [10], due to the loss of biodegradable materials and reduced microbial activity. By the end of the composting process, in the maturation phase, the lower compost temperature indicated that microbial activity had diminished due to the reduction in biodegradable compounds.

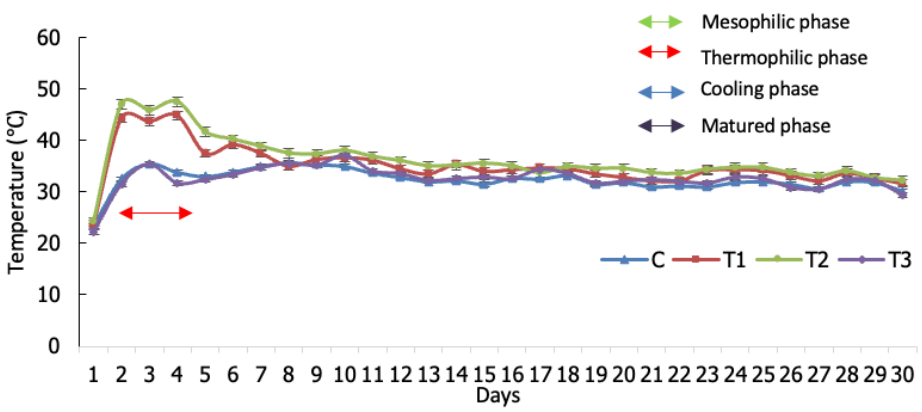


Fig. 3. Temperature recorded for different treatments over the 30-day composting period

3.2.2 pH

Figure 4 shows the changes in pH across the different treatments during the 30-day composting period. The results indicate that the initial pH of all compost treatments was acidic, with pH values of 6.00, 6.69, 5.77, and 6.49 for treatments C, T1, T2, and T3, respectively. However, the pH values decreased from day 1 to day 10 due to the presence of organic acids in the food waste [23] and the production of nitrogen, which is essential for pathogen and insect egg/nymph destruction [24]. As the composting process progressed, the pH gradually increased, reaching the highest value on the final day of composting: 7.25 for treatment T2, and 6.72, 6.89, and 6.62 for treatments C, T1, and T3, respectively. The increase in pH during the composting process can be attributed to the production of ammonia, which is closely related to the degradation of proteins in the sample and the breakdown of organic acids [25], or the biochemical conversion of organic nitrogen into free ammonia [26].

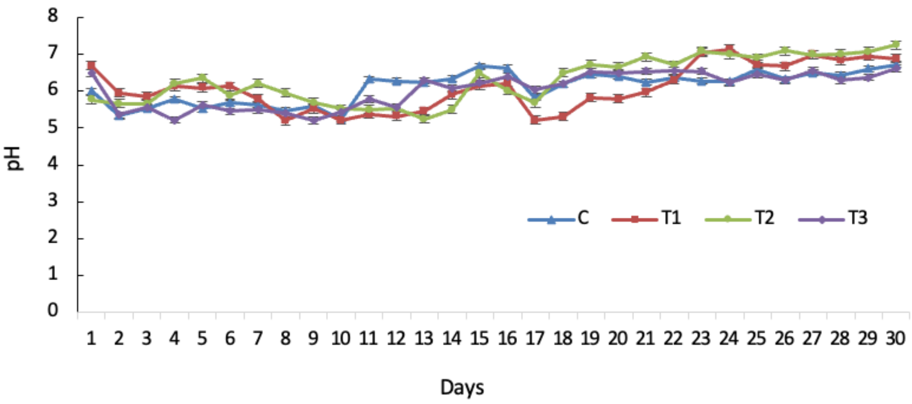


Fig. 4. pH values for different treatments over the 30-day composting period

According to Jain and Kalamdhad [27], the optimal pH range for composting is between 7 and 8.5, while Zahari *et al*., [28] state that the optimal pH range for microbial growth in composting is between 5.5 and 9.5. Based on the findings of this study, it can be concluded that all treatments achieved an optimal pH range for microbial growth, but only treatment T2 reached the optimal pH range for compost maturity. The acidity or pH level is a critical factor for the growth of microorganisms involved in the composting process. Monitoring the pH of compost serves as an indicator of the decomposition process. Microbes typically thrive in neutral to slightly acidic conditions, with a pH range of 6 to 8. During the decomposition phase, organic acids are formed, leading to a drop in pH [23]. The subsequent phase involves the transformation of organic acids, which are then utilized by other microbes, bringing the pH back to neutral, thereby facilitating compost maturation. The increase in pH is potentially linked to the release of ammonia gas [23].

3.2.3 Moisture content

Figure 5 shows the comparison of the average moisture content across treatments C, T1, T2, and T3. The graph indicates that the average moisture range for treatment T1 was between 65.75% and 72.96%, while for treatment T2, it ranged from 65.99% to 72.85% throughout the composting process. Meanwhile, treatment C exhibited the highest average moisture range, from 73.93% to 82.31%, followed by treatment T3, which ranged from 54.40% to 81.45%.

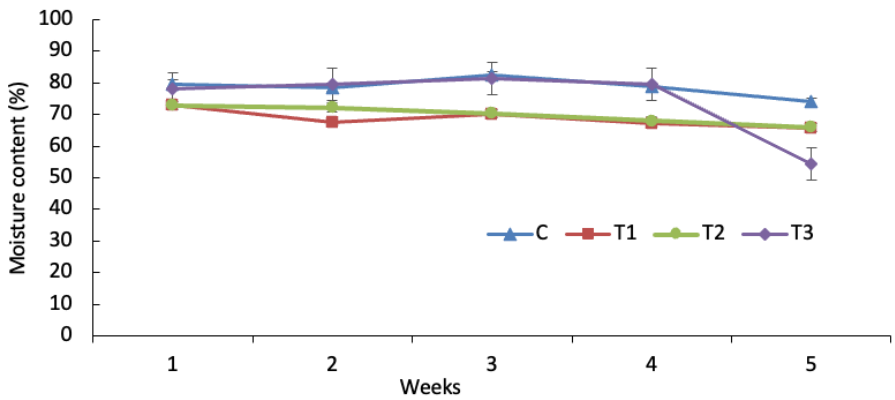


Fig. 5. Percentage of moisture content over the 30-day composting period

According to Li *et al.,* [29], a higher initial moisture content (65%) is more suitable for higher temperatures, longer high-temperature retention, and the production of more stable final compost, even though the optimal initial moisture content for composting typically ranges from 55% to 65%. Moisture levels are maintained at appropriate levels to ensure effective composting, as moisture has a significant impact on microbial activity and temperature [22]. When compared to other studies by Kalamdhad and Kazmi [30], and Villegas and Huilinir [31], the moisture content results are consistent with the findings of this study, showing a gradual reduction in moisture content throughout the composting process. The decrease in moisture content is due to the high heat generation during the composting process, which leads to higher water loss. In this study, the moisture content across all treatments ranged between 70% and 80%, providing a moist environment that is conducive to microbial growth.

3.2.4 Microbial population

Figure 6 shows the microbial population for different treatments over the 30-day composting period. Throughout the composting process, the microbial population was higher in the treatments containing sawdust, namely T1 and T2, compared to the other treatments, C and T3. Initially, the microbial populations in the compost materials for all treatments (C, T1, T2, and T3) were similar on day 1, with populations of 4.51×10^7, 5.82×10^7, 5.15×10^7, and 4.85×10^7 CFU/mL, respectively. This similarity in initial microbial population can be attributed to the fact that the compost materials used for all treatments were sourced from the same origin.

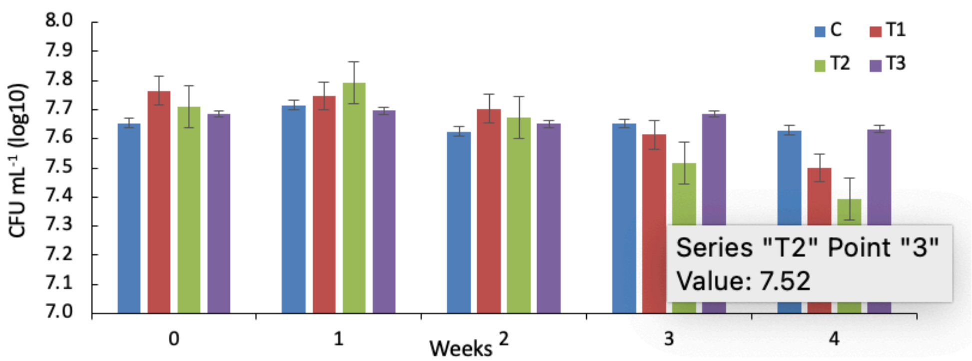


Fig. 6. Microbial population in different treatments over the 30-day composting period

The microbial population in T2 exhibited the highest value during week 1, as shown in Figure 4.6. The data obtained is consistent with the study by Zhang and Sun [32], which indicated that microbial populations were higher in treatments containing sawdust compared to those without sawdust. In week 2, all treatments showed a decline in microbial population, and subsequently, the microbial population decreased gradually until the end of the process in week 4. This decline indicates that microbial activity in the composting process diminished as the compost product matured and stabilized [32]. By the end of the composting period, microbial populations varied across the treatments. For treatments C and T3, microbial populations were nearly identical, at 4.26×10^7 and 4.30×10^7 CFU/mL, respectively. In contrast, microbial populations in treatments T1 and T2 were 3.17×10^7 and 2.48×10^7 CFU/mL, respectively. An increase in microbial population accelerates the decomposition of compost materials during the composting process [32]. The results of this study suggest that the combination of food waste and sawdust effectively enhances microbial populations. Sawdust possesses a macro-porous structure that provides a high surface area for microbial attachment and reproduction, thus improving aeration and creating a favorable micro-physical environment for microbial growth [33]. Additionally, sawdust serves as a carbon and nitrogen source for microorganisms [34].

3.3 Seed Germination Index (GI)

Before applying compost to the soil, it is crucial to assess its quality, including its stability and maturity. The Seed Germination Index (GI) is a sensitive parameter commonly used to evaluate the toxicity of compost to seedlings and to assess its maturity [35]. According to Luo et al., [36], the Seed Germination Index (GI) has been widely adopted as a biological indicator for evaluating compost phytotoxicity and maturity. Immature and unstable compost can negatively affect seed germination, plant growth, and soil ecosystem balance [36]. This is typically due to a reduction in available oxygen and nitrogen, or the presence of phytotoxic substances [37]. In this study, two types of seeds—mung bean and mustard—were selected for the GI test. Observations were made after 5 days of seed sowing. According to Li *et al.*, [38], compost maturity is classified into three categories based on the GI value: immature (<80%), mature (80-90%), and very mature (>90%). The results of the seed germination index for mung bean and mustard are discussed in detail in section 3.3.1.

3.3.1 Mung bean and mustard seeds

The seed germination index (GI) for mung bean and mustard seeds from different compost treatments is shown in Figure 7 (c).

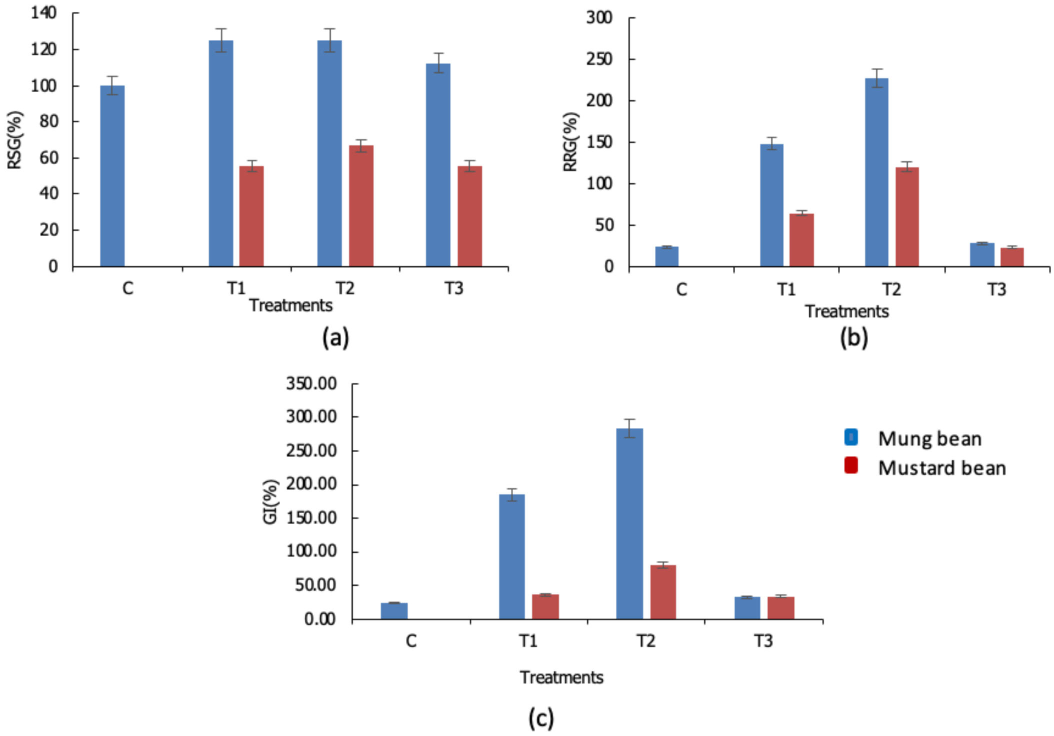


Fig. 7. Histograms of calculated inputs for seed germination tests (a) Relative Seed Germination Percentage (RSG)(b) Relative Root Growth Percentage (RRG) (c) Seed Germination Index (GI)

The results indicate the relative seed germination percentage (RSG) for mung bean in Figure 7 (a) as follows: 100.00% for treatment C, 125.00% for T1, 125.00% for T2, and 112.50% for T3. For mustard seeds, the RSG percentage for C was 0%, 55.56% for T1, 66.67% for T2, and 55.56% for T3. As shown in Figure 7 (b), the relative root growth (RRG) percentage for mung bean was 24.29% for C, 148.00% for T1, 226.86% for T2, and 28.86% for T3. For mustard seeds, the RRG percentage was 0% for C, 64.71% for T1, 120.59% for T2, and 23.53% for T3. Treatment T2 recorded the highest GI value, with 283.56% for mung bean and 80.39% for mustard seeds, followed by T1 with 185.00% for mung bean and 35.95% for mustard seeds. Meanwhile, treatments C and T3 showed values of 24.29% for mung bean and 0% for mustard seeds, and 32.47% for mung bean and 33.63% for mustard seeds, respectively. According to Li *et al.*, [38] a GI value exceeding 90% indicates very mature compost. The increase in GI values suggests a reduction in phytotoxic content during the decomposition of toxic substances in the composting process [39]. The reduction in phytotoxicity in the compost is likely due to the breakdown of fatty materials, soluble phenolic compounds, and changes in organic acid levels [40]. In this study, the GI values for the compost exceeded 80%, indicating that the compost was mature and free of phytotoxic compounds. Therefore, it can be concluded that the compost products from treatments T1 and T2 are phytotoxic-free and very mature, while treatments C and T3 contain phytotoxic compounds and are not mature. Figures 8 (a - e) and Figure 9 (a - e) show the germination of mung bean and mustard seeds after 5 days using compost dissolved in distilled water at a 1:10 ratio from the different treatments.

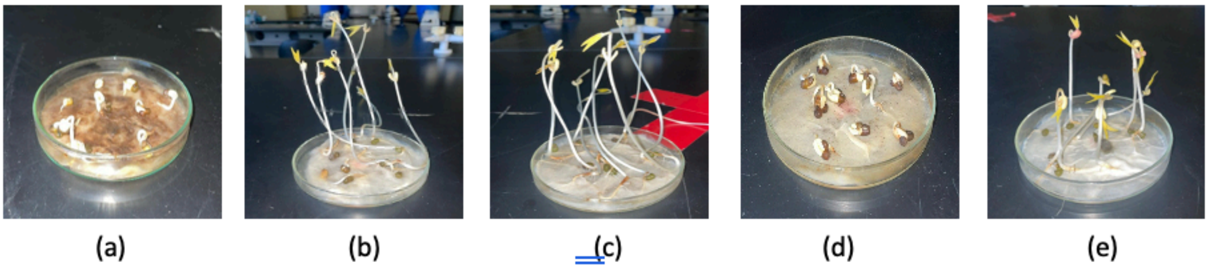


Fig. 8. Germination of mung bean seeds (a) Treatment C (b) Treatment T1 (c) Treatment T2 (d) Treatment T3 (e) Control

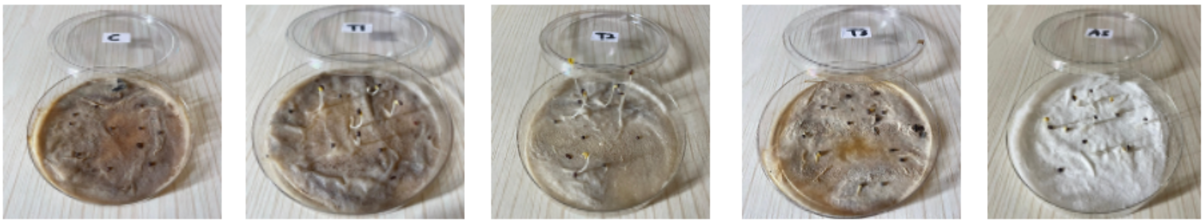


Fig. 9. Germination of mustard seeds (a) Treatment C (b) Treatment T1 (c) Treatment T2 (d) Treatment T3 (e) Control.

3.4 Statistical Analysis (Comparison between different composting treatments and seed germination index)

The germination index percentages for green bean and mustard seeds for each treatment were obtained. An analysis was performed using ANOVA: Single Factor to determine the comparison between different composting treatments and the seed germination index. 2 and 3 present the data obtained for the comparison of different composting treatments with seed germination index.

Table 2
Results of the ANOVA: Single Factor analysis for different composting treatments with the green bean germination index

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	355.185	3	118.395	65.518	1.18×10^{-14}	2.866
Within Groups	65.054	36	1.807			
Total	420.239	39				

Table 3
Results of the ANOVA: Single Factor analysis for different composting treatments with the mustard seed germination index

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.875	3	1.292	6.546	0.001	2.866
Within Groups	7.104	36	0.197			
Total	10.979	39				

Based on Tables 2 and 3, the germination of mung bean and mustard seeds showed a highly significant comparison between the different composting treatments with respect to the seed germination index. The p-value for mung bean was $P = 0.000$ ($P < 0.05$); $F = 65.518$, while the p-value for mustard seed was $P = 0.001$ ($P < 0.05$); $F = 6.546$. Therefore, these results confirm that there are significant differences in the compost produced by each type of composting treatment.

4. Conclusions

In this study, the composting of organic waste over a 30-day period demonstrated that Treatment T2 produced the best compost compared to the other treatments. This was evidenced by changes in the color, texture, and odor of the compost, which serve as indicators of compost maturity. Seed germination index (GI) tests on mung bean and mustard seeds showed that the compost produced was mature, with a GI value exceeding 90% after the composting period. Based on the findings of this study, Treatment T2, which involved the use of organic waste, sawdust, and the application of active aeration in the reactor, produced compost of high quality and maturity.

4. Limitation and Future Research Direction

This study on biocomposting of organic waste using a vertical reactor with different treatments (control, sawdust, aeration, and their combinations) faces several limitations. This include the limited diversity of raw materials (focused primarily on food waste and sawdust), small-scale experimentation that may not translate to larger systems, and the study's primary focus on physical and chemical parameters without delving into microbial diversity or safety aspects like heavy metal content. Additionally, the environmental impact, such as greenhouse gas emissions, and economic feasibility were not evaluated comprehensively. The study also uses a single aeration mode, leaving potential for optimization unexplored.

Future research should integrate diverse organic waste types, optimize aeration rates and modes, and analyze microbial diversity to enhance the composting process. Additionally, studies should quantify greenhouse gas emissions, test scalability for larger systems, and evaluate long-term effects of the compost on soil and agriculture. Addressing safety concerns, including pathogen and contaminant presence, alongside a cost-benefit analysis, will support real-world adoption and sustainability of the system. These steps can make composting with vertical reactors more effective, scalable, and environmentally beneficial.

References

[1] Abd Manaf, Latifah, Mohd Armi Abu Samah, and Nur Ilyana Mohd Zukki. "Municipal solid waste management in Malaysia: Practices and challenges." *Waste management* 29, no. 11 (2009): 2902-2906. doi: 10.1016/J.WASMAN.2008.07.015.

[2] Yow, Hui Ming, Amir Abdul Razak, and Adel Aboulqasim Alheemar. "Current energy recycling technology for agricultural waste in Malaysia." *Progress in Energy and Environment* (2024): 11-22. doi: 10.37934/PROGEE.27.1.1122.

[3] Orhorhoro, Ejiroghene Kelly, and Oghenekevwe Oghoghorie. "Enhancing biogas yield through anaerobic co-digestion of animal manure and seaweed." *Progress in Energy and Environment* (2024): 1-22. doi: 10.37934/PROGEE.28.1.122.

[4] Wang, Yumei, Zengwei Yuan, and Ya Tang. "Enhancing food security and environmental sustainability: A critical review of food loss and waste management." *Resources, Environment and Sustainability* 4 (2021): 100023. doi: 10.1016/J.RESENV.2021.100023.

[5] Gao, Mengchun, Fangyuan Liang, An Yu, Bing Li, and Lijuan Yang. "Evaluation of stability and maturity during forced-aeration composting of chicken manure and sawdust at different C/N ratios." *Chemosphere* 78, no. 5 (2010): 614-619. doi: 10.1016/J.CHEMOSPHERE.2009.10.056.

[6] Diaz, M. J., E. Madejon, F. Lopez, R. Lopez, and F. Cabrera. "Optimization of the rate vinasse/grape marc for co-composting process." *Process Biochemistry* 37, no. 10 (2002): 1143-1150. doi: 10.1016/S0032-9592(01)00327-2.

[7] Shen, Yujun, Limei Ren, Guoxue Li, Tongbin Chen, and Rui Guo. "Influence of aeration on CH4, N2O and NH3 emissions during aerobic composting of a chicken manure and high C/N waste mixture." *Waste management* 31, no. 1 (2011): 33-38. doi: 10.1016/J.WASMAN.2010.08.019.

[8] Ge, Jinyi, Guangqun Huang, Jing Huang, Jianfei Zeng, and Lujia Han. "Modeling of oxygen uptake rate evolution in pig manure–wheat straw aerobic composting process." *Chemical Engineering Journal* 276 (2015): 29-36.doi: 10.1016/J.CEJ.2015.04.067.

[9] Guo, Rui, Guoxue Li, Tao Jiang, Frank Schuchardt, Tongbin Chen, Yuanqiu Zhao, and Yujun Shen. "Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost." *Bioresource technology* 112 (2012): 171-178. doi: 10.1016/J.BIORTECH.2012.02.099.

[10] Zahrim, A. Y., M. Darwis, D. Samantha, AZ Siti Hasanah, SA Nur Aqeela, L. Junidah, S. Sariah, and R. Mariani. "Composting of food waste in passive aerated bioreactor with turning mode." In *IOP Conference Series: Materials Science and Engineering*, vol. 1195, no. 1, p. 012001. IOP Publishing, 2021. doi: 10.1088/1757-899X/1195/1/012001.

[11] Mbuligwe, S. E., G. R. Kassenga, Meniseny E. Kaseva, and Esnati J. Chaggu. "Potential and constraints of composting domestic solid waste in developing countries: findings from a pilot study in Dar es Salaam, Tanzania." *Resources, conservation and recycling* 36, no. 1 (2002): 45-59. doi: 10.1016/S0921-3449(02)00009-5.

[12] Alkoaik, Fahad N. "Integrating aeration and rotation processes to accelerate composting of agricultural residues." *PLoS One* 14, no. 7 (2019): e0220343. doi: 10.1371/JOURNAL.PONE.0220343.

[13] Fischer, Daniel, and Bruno Glaser. "Synergisms between compost and biochar for sustainable soil amelioration." *Management of organic waste* 1 (2012): 167-198. doi: 10.5772/31200.

[14] Sulfiana, Sulfiana. "Analisis Kualitas Kompos Limbah Organik Rumah Tangga Berdasarkan Variasi Dosis Bioaktivator MOL Limbah Tomat= Analysis of the Quality of Household Organic Waste Compost Based on Variations in Dose of Tomato Waste MOL Bioactivator." PhD diss., Universitas Hasanuddin, 2022.doi: 10.56338/PROMOTIF.V12I2.2883.

[15] "Penggunaan Kompos Dalam Mengembalikan Kesuburan Tanah | FAKULTI REKABENTUK DAN SENIBINA." Accessed: Nov. 27, 2024. [Online]. Available: https://frsb.upm.edu.my/artikel/penggunaan_kompos_dalam_mengembalikan_kesuburan_tanah-69919

[16] Beck-Friis, Barbro, Sven Smårs, Håkan Jönsson, and Holger Kirchmann. "Gaseous emissions of carbon dioxide, ammonia and nitrous oxide from organic household waste in a compost reactor under different temperature regimes." (2001): 423-430. doi: 10.1006/JAER.2000.0662.

[17] N. H. M. Sabiani and F. A. H. Asaari, "Kajian Perbandingan Kualiti Kompos Daripada Sisa Taman Menggunakan Pelbagai Kaedah Pengkomposan.," 2007.

[18] Petric, Ivan, Edisa Avdihodžić, and Nidret Ibrić. "Numerical simulation of composting process for mixture of organic fraction of municipal solid waste and poultry manure." *Ecological engineering* 75 (2015): 242-249. doi: 10.1016/J.ECOLENG.2014.12.003.

[19] Alpandari, Heny, Tangguh Prakoso, Agung Astuti, and Mulyono Mulyono. "Pemanfaatan Isolat Bakteri Tongkol Jagung Sebagai Bioaktivator Alami Dalam Pengomposan Tongkol Jagung (Zea mays)." *Muria Jurnal Agroteknologi (MJ-Agroteknologi)* 1, no. 1 (2022): 1-7. doi: 10.24176/MJAGROTEK.V1I1.8215.

[20] Paradelo, Remigio, Ana Belén Moldes, and María Teresa Barral. "Evolution of organic matter during the mesophilic composting of lignocellulosic winery wastes." *Journal of environmental management* 116 (2013): 18-26. doi: 10.1016/J.JENVMAN.2012.12.001.

[21] Hubbe, Martin A., Mousa Nazhad, and Carmen Sanchez. "Composting as a way to convert cellulosic biomass and organic waste into high-value soil amendments: a review." (2010): 2808-2854. doi: 10.15376/BIORES.5.4.2808-2854.

[22] Tiquia, S. M., N. F. Y. Tam, and I. J. Hodgkiss. "Effects of composting on phytotoxicity of spent pig-manure sawdust litter." *Environmental pollution* 93, no. 3 (1996): 249-256. doi: 10.1016/S0269-7491(96)00052-8.

[23] Kumar, Mathava, Yan-Liang Ou, and Jih-Gaw Lin. "Co-composting of green waste and food waste at low C/N ratio." *Waste management* 30, no. 4 (2010): 602-609. doi: 10.1016/J.WASMAN.2009.11.023.

[24] Setyaningsih, Endang, Dwi Setyo Astuti, and Rina Astuti. "Kompos daun solusi kreatif pengendali limbah." *Bioeksperimen: Jurnal Penelitian Biologi* 3, no. 2 (2017): 45-51. doi: 10.23917/BIOEKSPERIMEN.V3I2.5181.

[25] Liu, Dongyang, Ruifu Zhang, Hongsheng Wu, Dabing Xu, Zhu Tang, Guanghui Yu, Zhihui Xu, and Qirong Shen. "Changes in biochemical and microbiological parameters during the period of rapid composting of dairy manure with rice chaff." *Bioresource technology* 102, no. 19 (2011): 9040-9049. doi: 10.1016/J.BIORTECH.2011.07.052.

[26] Altieri, Roberto, Alessandro Esposito, and Tan Nair. "Novel static composting method for bioremediation of olive mill waste." *International Biodeterioration & Biodegradation* 65, no. 6 (2011): 786-789. doi: 10.1016/J.IBIOD.2011.05.002.

[27] Jain, Mayur Shirish, and Ajay S. Kalamdhad. "Drum composting of nitrogen-rich Hydrilla Verticillata with carbon-rich agents: Effects on composting physics and kinetics." *Journal of environmental management* 231 (2019): 770-779. doi: 10.1016/J.JENVMAN.2018.10.111.

[28] Zahari, Nur Zaida, Piakong Mohd Tuah, Nur Hazwani Che Zulkifli, and Fera Nony Cleophas. "Composting of Oil Palm Empty Fruit Bunches by Microbial Inoculant." *Int. J. Technol* 14, no. 5 (2023): 1081-1092. doi: 10.14716/IJTECH.V14I5.5907.

[29] Li, Xiujin, Ruihong Zhang, and Yunzhi Pang. "Characteristics of dairy manure composting with rice straw." *Bioresource Technology* 99, no. 2 (2008): 359-367. doi: 10.1016/J.BIORTECH.2006.12.009.

[30] Kalamdhad, Ajay S., Yatish K. Singh, Muntjeer Ali, Meena Khwairakpam, and Absar Ahmad Kazmi. "Rotary drum composting of vegetable waste and tree leaves." *Bioresource Technology* 100, no. 24 (2009): 6442-6450. doi: 10.1016/J.BIORTECH.2009.07.030.

[31] Villegas, Manuel, and Cesar Huiliñir. "Biodrying of sewage sludge: Kinetics of volatile solids degradation under different initial moisture contents and air-flow rates." *Bioresource technology* 174 (2014): 33-41. doi: 10.1016/J.BIORTECH.2014.09.136.

[32] Zhang, Lu, and Xiangyang Sun. "Influence of bulking agents on physical, chemical, and microbiological properties during the two-stage composting of green waste." *Waste Management* 48 (2016): 115-126. doi: 10.1016/J.WASMAN.2015.11.032.

[33] Koivula, Niina, Tarja Räikkönen, Sari Urpilainen, Jussi Ranta, and Kari Hänninen. "Ash in composting of source-separated catering waste." *Bioresource Technology* 93, no. 3 (2004): 291-299. doi: 10.1016/J.BIORTECH.2003.10.025.

[34] Kato, Kotaro, and Nobuaki Miura. "Effect of matured compost as a bulking and inoculating agent on the microbial community and maturity of cattle manure compost." *Bioresource Technology* 99, no. 9 (2008): 3372-3380. doi: 10.1016/J.BIORTECH.2007.08.019.

[35] Wong, J. W. C., K. F. Mak, N. W. Chan, A. Lam, M. Fang, L. X. Zhou, Q. T. Wu, and X. D. Liao. "Co-composting of soybean residues and leaves in Hong Kong." *Bioresource Technology* 76, no. 2 (2001): 99-106. doi: 10.1016/S0960-8524(00)00103-6.

[36] Luo, Yuan, Jie Liang, Guangming Zeng, Ming Chen, Dan Mo, Guoxue Li, and Difang Zhang. "Seed germination test for toxicity evaluation of compost: Its roles, problems and prospects." *Waste Management* 71 (2018): 109-114. doi: 10.1016/J.WASMAN.2017.09.023.

[37] Bernal, M. P[illegible], J. A. Alburquerque, and Raúl Moral. "Composting of animal manures and chemical criteria for compost maturity assessment. A review." *Bioresource technology* 100, no. 22 (2009): 5444-5453. doi: 10.1016/J.BIORTECH.2008.11.027.

[38] Li, Xu, Xiao-Shuang Shi, Zhi-Man Yang, Xiao-Hui Xu, and Rong-Bo Guo. "Effects of recyclable ceramsite as the porous bulking agent during the continuous thermophilic composting of dairy manure." *Journal of Cleaner Production* 217 (2019): 344-351. doi: 10.1016/J.JCLEPRO.2019.01.148.

[39] He, Miao-miao, Guang-ming Tian, and Xin-qiang Liang. "Phytotoxicity and speciation of copper, zinc and lead during the aerobic composting of sewage sludge." *Journal of Hazardous Materials* 163, no. 2-3 (2009): 671-677. doi: 10.1016/J.JHAZMAT.2008.07.013.

[40] Piotrowska-Cyplik, Agnieszka, Łukasz Chrzanowski, Paweł Cyplik, Jacek Dach, Anna Olejnik, Justyna Staninska, Jakub Czarny, Andrzej Lewicki, Roman Marecik, and Jolanta Powierska-Czarny. "Composting of oiled bleaching earth: Fatty acids degradation, phytotoxicity and mutagenicity changes." *International Biodeterioration & Biodegradation* 78 (2013): 49-57. doi: 10.1016/J.IBIOD.2012.12.007.