Ecotoxicology and Environmental Safety 263 (2023) 115255

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

# Composting and vermicomposting of sewage sludge at various C/N ratios: Technological feasibility and end-product quality

Bayu Dume [a,*], Ales Hanc [a], Pavel Svehla [a], Pavel Michal [a], Abraham Demelash Chane [a], Abebe Nigussie [b]

[a] Czech University of Life Sciences, Faculty of Agrobiology, Food, and Natural Resources, Department of Agro-Environmental Chemistry and Plant Nutrition, Kamycka 129, Prague 16500, Czech Republic
[b] Jimma University, College of Agriculture, 307, Jimma, Ethiopia

ARTICLE INFO

Edited by Dr G Liu

*Keywords:*
Sewage sludge
Vermicomposting
*Eisenia andrei*
Composting
C/N ratio

ABSTRACT

Even though sewage sludge (SS) contains a high level of pollutants, it is rich in essential plant nutrients and has the potential to enhance soil fertility. However, the SS must be further treated through pre-composting plus vermicomposting to make it safe for use on food crops. More research and data are needed to determine how different carbon-to-nitrogen ratios (C/N) affect the feasibility and quality of composting vs vermicomposting of SS. Therefore, in this study we comprehensively evaluated the feasibility and end-product quality of compost and vermicompost produced from SS under different C/N ratios. SS was mixed with pelletized wheat straw (PWS) at various proportions to produce C/N ratios of 6:1, 18:1, 28:1, and 38:1, then pre-composted for 14 days followed by vermicomposting using the earthworm *Eisenia andrei* for 120 days. Agrochemical properties were measured at 0, 30, 60, 90, and 120 days. Results revealed significantly higher levels of agrochemicals in vermicompost compared to compost, including total potassium (37–88%) and magnesium (4.3–12%), nitrate nitrogen (71–98%), available potassium (53–88%), available phosphorus (79%), available magnesium (54–453%), available boron (48–303%), and available copper (2.5–82%). However, lower levels of ammonium nitrogen by (59–85%), available iron (2.3–51.3%), available manganese (29.7–52.2%), available zinc (10.5–29.8%), total carbon (0.75–4.5%), and total nitrogen (1.6–22.2%) were measured. Comparison of the various C/N ratios, showed that vermicompost with an 18:1 C/N ratio outperformed compost and demonstrated the highest earthworm population (165 pieces/kg). Thus, vermicomposting SS at an 18:1 C/N ratio is strongly recommended as a sustainable technology for producing high-quality vermicompost from SS.

## 1. Introduction

Sewage sludge (SS) is a by-product produced in large quantities during wastewater treatment processes. Because of the presence of pollutants such as organic chemicals and toxic heavy metals, and potential pathogens, raw SS is hazardous and raises serious environmental concerns about its use as a soil amendment (Hait and Tare, 2012). The amount of SS produced yearly rises in lockstep with the global urban population. Because of this increase and the problems associated with SS disposal, this product poses significant challenges in several regions of the world (Mousavi, 2022). Mateo-Sagasta et al. (2015) estimated that the total SS volume produced in Europe (2010), China (2006), and the United States (2004) was 9, 3, and 6.5 million tons of dry matter per year, respectively. Composting and vermicomposting of SS for soil amendment is typically the most efficient and cost-effective treatment method and allows farmers to utilize less chemical fertilizer. Since it has a high content of organic matter and essential plant nutrients, SS is best suited as a bio-fertilizer (Guilayn et al., 2019). It has been widely recognized that SS helps to improve the soil's physical, chemical, and biological characteristics (Alvarenga et al., 2015). Because of the occurrence of specific pollutants, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), endocrine disruptors (EDs), pharmaceutical residues (PRs), toxic heavy metals (e.g., Pb, Cd, Ni, Co, and Cr), and potentially pathogenic organisms (bacteria, viruses, and parasites), it is necessary to treat the SS prior to agricultural use to remove or sequester toxic substances and kill pathogens (Lillenberg et al., 2010). Some studies have been conducted to assess the use of aerobic composting and vermicomposting to transform the sludge into a

* Corresponding author.
*E-mail address:* dumebayu@gmail.com (B. Dume).

https://doi.org/10.1016/j.ecoenv.2023.115255
Received 7 February 2023; Received in revised form 5 June 2023; Accepted 12 July 2023
Available online 19 July 2023
0147-6513/

safe product for agricultural application (Kinney et al., 2012; García-Gómez et al., 2014; Singh et al., 2020).

Composting and vermicomposting are two common bioorganic methods for transforming organic waste materials into valuable biofertilizers. In composting, environmentally friendly bacteria and fungi break down the waste matter and produce stable organic material with enhanced biochemical and physical properties (Hait and Tare, 2012). In vermicomposting, earthworms ingest the organic material, converting it into nutrient-rich castings that can be used as a valuable soil amendment (Liu et al., 2012). As a bio-oxidative process that involves earthworms and microorganisms, vermicomposting is gaining popularity due to its versatility (Soobhany, 2019; Lv et al., 2018; Nigussie et al., 2016). Composting is also recognized as an environmentally friendly process in which microorganisms degrade organic matter and turn it into a sanitized agricultural soil amendment. The sanitization process is associated with the early aerobic phase of composting when the temperature in the composter increases to 45–70 °C (Bernal et al., 2009). This elevated temperature creates conditions inhospitable to many pathogens and helps eliminate potential health risks associated with composting some organic materials like sludge.

Fresh sewage sludge should not be used for vermicomposting since it is anaerobic, contains substances toxic to earthworms, and also has excessively high concentrations of ammonia ($NH_3$) and methane ($CH_4$) (Awiszus et al., 2018). SS pre-composting at high temperatures is needed to avoid harm to earthworms and to remove excess ammonia (Kaushik and Garg, 2003). The material should be aerated and stabilized during the pre-composting process, reducing moisture content and inactivating pathogens (Yadav et al., 2012; Yadav and Garg, 2016; Malinska et al., 2016).

Studies have been conducted comparing the results of composting and vermicomposting (Lazcano et al., 2008; Rékási et al., 2019; Tognetti et al., 2007) and vermicompost has been shown to have a greater market acceptance than compost because of its better performance and the significantly greater availability of organic matter and plant nutrients (Tognetti et al., 2005). Vermicompost contains more humic substances and stable organic compounds than traditional compost, and also has a more comprehensive impact on nutrient management because of the slower nutrient release and the presence of higher levels of plant hormones that encourage growth (Rékási et al., 2019). Researchers have compared compost with vermicompost by using the same raw materials and conditions (Fornes et al., 2012; Hanc and Dreslova, 2016). Thus, for this study, we used the same raw materials, sewage sludge combined with pelletized wheat straw, to compare the quality of the final products.

Because of their importance as primary nutrients needed for microbial activity, the carbon and nitrogen levels, and especially the ratio of carbon to nitrogen (C/N) are regarded as crucial factors influencing compost quality (LV et al., 2018; Sánchez-Monedero et al., 2010; Zhang et al., 2016) and how long it takes for the compost to reach maturity (Tripetchkul et al., 2012; Guo et al., 2012). Evidence has shown that a C/N ratio of 25–35 is optimal for composting microbes to remain stable and active (Akratos et al., 2017). According to Kumar et al. (2010), the ideal starting C/N ratio range for composting is 25–30; however, Vochozka et al. (2017) argued that improved global standards necessitated a C/N range of 20–30. A high C/N ratio causes the process to start slowly and take longer to produce finished compost, whereas a low initial C/N ratio results in high ammonia ($NH_3$) emissions and increased nitrogen loss (Oudart, 2013). A too low initial C/N of 15 significantly negatively affected several agrochemical properties during the process (Huang et al., 2004). El-mrini et al. (2022) reported that a C/N ratio of 25 during composting decreased copper (Cu) and zinc (Zn) mobility, but increased total metal ion content, which could alter urease enzyme activity (Wu et al., 2017). Other researchers found significant effects of C/N on pathogen reduction (Macias-Corral et al., 2019). The C/N ratio can be adjusted by choosing the appropriate combination of compost materials and adding co-substrates to attain the desired final ratio (Akratos et al., 2017). However, it is still unclear how different C/N ratios affect compost quality and the time needed to produce it, and more studies are needed to determine how different C/N ratios affect the quality of compost vs vermicompost and the feasibility of producing a good product from a given substrate. Therefore, this study comprehensively evaluated the feasibility and end-product quality of compost and vermicompost produced under different C/N ratios.

## 2. Materials and methods

### 2.1. Initial raw materials and earthworms

The unstabilized, freshly collected sewage sludge used in this experiment was obtained from a wastewater treatment plant in a small town in the Czech Republic. It had a dry matter content of 13.3%, a pH-$H_2O$ of 6.9, and electrical conductivity (EC) of 0.6 mS/cm. The SS material was 32.9% C and 5.4% N (C/N = 6.1), and per kg of dry weight contained, 5002 mg of potassium (K), 4809 mg of magnesium (Mg), and 15,996 mg of phosphorus (P). Dried pelletized wheat straw (PWS) was obtained from the Granofyt Co., Ltd.(Chrášťany, Czechia). It had a diameter of 10 mm and a dry matter content of 21.2%, a pH-$H_2O$ of 8.3, and an EC of 0.68 mS/cm, with 42.6% C and 0.8% N (C/N = 53.2). Per kg of dry weight, the PWS contained 5953 mg of K, 935 mg of Mg, and 704 mg of P. Because of the low moisture content of the PWS, it was mixed with hot water (60 °C) at a 1:4 (w/v) ratio before use. Earthworms were collected from a private vermiculture stock in the Czech Republic with apple pomace as survival medium. The epigeic earthworm species, *Eisenia andrei*, was used in the experiments because of its high tolerance for toxic substances in SS, adaptability to a relatively wide range of pH, moisture, and temperature levels, a high growth rate, and ability to convert semi-composted biomass into stable products, (Gupta and Garg, 2011; Yadav and Garg, 2016).

### 2.2. Experimental set-up

#### 2.2.1. Pre-composting

The experiment included four different initial C/N ratios (1) 6:1, (2) 18:1, (3) 28:1, and (4) 38:1 achieved by mixing SS with PWS in different proportions: (1) 100% SS, (2) 75% SS + 25% PWS, (3) 50% SS + 50% PWS, and (4) 25% SS + 75% PWS. On a dry-weight basis, this results in different ratios of SS to PWS: Mix1 (4:0), Mix2 (3:1), Mix3 (2:2), and Mix4 (1:3). Three replicates were run for each condition (n = 3). Before vermicomposting, all mixtures were pre-composted for 14 days in 70-L laboratory reactors with 56-cm diameters. The pre-composting phase is crucial since this breaks down highly unstable materials, decreases the concentration of volatile acids, and stabilizes the temperature conditions for the earthworms (Zziwa et al., 2021; Karwal and Kaushik, 2020; Mainoo et al., 2009).

#### 2.2.2. Vermicomposting

The vermicomposting method used was a technique which had been proved to give the optimal environmental and technical conditions for the process (Hanc et al., 2022). After pre-composting for 14 days, the variants VC1, VC2, VC3 and VC4 for Mix1 (4:0), Mix2 (3:1), Mix3 (2:2) and Mix4 (1:3) SS:PWS, respectively, were transferred to worm bins (40 ×40×15 cm) for vermicomposting in a specially adapted laboratory under controlled conditions of temperature (22 °C) and relative humidity (80%) and vermicomposted for 120 days. Each worm bin received adult *Eisenia andrei* earthworms with an average weight of 0.2 g/piece and number of earthworms at 125 pieces/L of substrate. The earthworms weighed 25 g per kilogram of substrate. The substrate (3 L grape marc) containing the earthworms were put inside the plastic container from the side to ensure earthworm survival and quickly return them to favourable conditions. A 6-mm mesh separated the materials, which were sprayed with water every two days to keep the moisture content of the material at 70–80%.

### 2.2.3. Composting

The same vermicomposting mixtures were used for the composting experiment, which was also run for 120 days. The various SS:PWS formulations, Mix1 (4:0), Mix2 (3:1), Mix3 (2:2), and Mix4 (1:3), labelled C1, C2, C3, and C4, respectively, were transferred to aerobic composters (fermenter barrels) with a working volume of 70 L and a diameter of 56 cm, which were constructed with the aim to ensure optimal conditions for composting (Hanc et al., 2022). For optimal composting, aeration was provided to promote the growth and activity of aerobic microorganisms, which require oxygen to carry out the decomposition process efficiently (Wang et al., 2021). In vermicomposting, aeration is not required since earthworms burrow through the organic materials and create tunnels that provide oxygen to the microorganisms involved in the decomposition process. Earthworms can tolerate lower oxygen levels than aerobic microorganisms, so aeration is not as critical in vermicomposting as it is in composting (Pathma et al., 2012). Air was pumped from the bottom through the composted materials using an air compressor and active aeration device. Batch aeration was performed on the mixtures for 5 min every half hour at a rate of 4 L of air per minute, followed by 3 min every half hour. The temperature probe was inserted from the composter's top to half the material height, and the temperature was recorded and stored in a data logger every hour. The leachate was collected and poured back into the composted material before sampling at the end of each month to achieve a closed loop of substances produced in the pile. Based on their experiments, Hanc et al. (2012) affirmed that these aeration conditions were optimal for good composting. Some studies compared the effectiveness of composting and vermicomposting without regard for container volume (Lazcano et al., 2008; Rékási et al., 2019). However, it is important to note that the results of composting and vermicomposting can vary depending on a number of factors, including the starting material, moisture content, temperature, and other environmental conditions (FAO, 2017). Thus, our study was performed with controlled temperature and humidity. The composting and vermicomposting experiments were conducted at the Czech University of Agricultural Research Station in Červený Újezd. The samples were then collected and analysed at the Czech University of Life Science's, Prague laboratories in the Faculty of Agrobiology, Food and Natural Resources, department of Agro-environmental Chemistry and Plant nutrition. The experimental study design is shown in Fig. 1.

### 2.3. Sampling and analysis of agrochemical properties

Representative composite samples (~150 g wet basis for every variant) were collected on days 0, 30, 60, 90, and 120 and then freeze-dried (−25 °C) for agrochemical analysis. In addition, 30 g samples were collected from each variant and frozen at 4 °C for later measurement of pH and electrical conductivity (EC). The following agrochemical parameters were analysed: pH, EC, total and available macronutrients (K, Mg, and P), mineral nitrogen (N-$NO_3^-$, N-$NH_4^+$), micronutrients (B, Cu, Fe, Mn and Zn), total nitrogen (TN) and total carbon (TC). The pH-$H_2O$ and EC values were determined using a WTW pH 340i and WTW Cond 730 (1:5 w/v dry basis), following the BSI EN 15933 (2012). Total concentrations of macronutrients, K, Mg, and P, were determined by decomposition in a closed system with microwave heating using an Ethos1 system (MLS GmbH, Germany). The contents of N-$NO_3^-$, N-$NH_4^+$, readily available macronutrients (K, Mg, and P), and available micronutrients (B, Cu, Fe, Mn, and Zn) were analysed using CAT solution (0.01 M $CaCl_2$ and 0.002 M diethylenetriamine pentaacetic acid (DTPA) at a ratio of 1:10 (w/v), according to BSI EN 13651 (2001). Optical emission spectrometry using an inductively-coupled plasma detector (ICP-OES, VARIAN VistaPro, Varian, Australia) with axial plasma configuration was used to determine total and available nutrient contents. To determine the C/N ratio, a CHNS Vario MacroCube (Elementar Analysensysteme GmbH, Germany) analyser was used according to Hanc et al. (2017). The CHNS Vario MacroCube analyser is a highly accurate and reliable instrument for determining total carbon and total nitrogen content. Earthworms and cocoons were hand-sorted, separated from the samples, counted, and then washed with water and weighed.

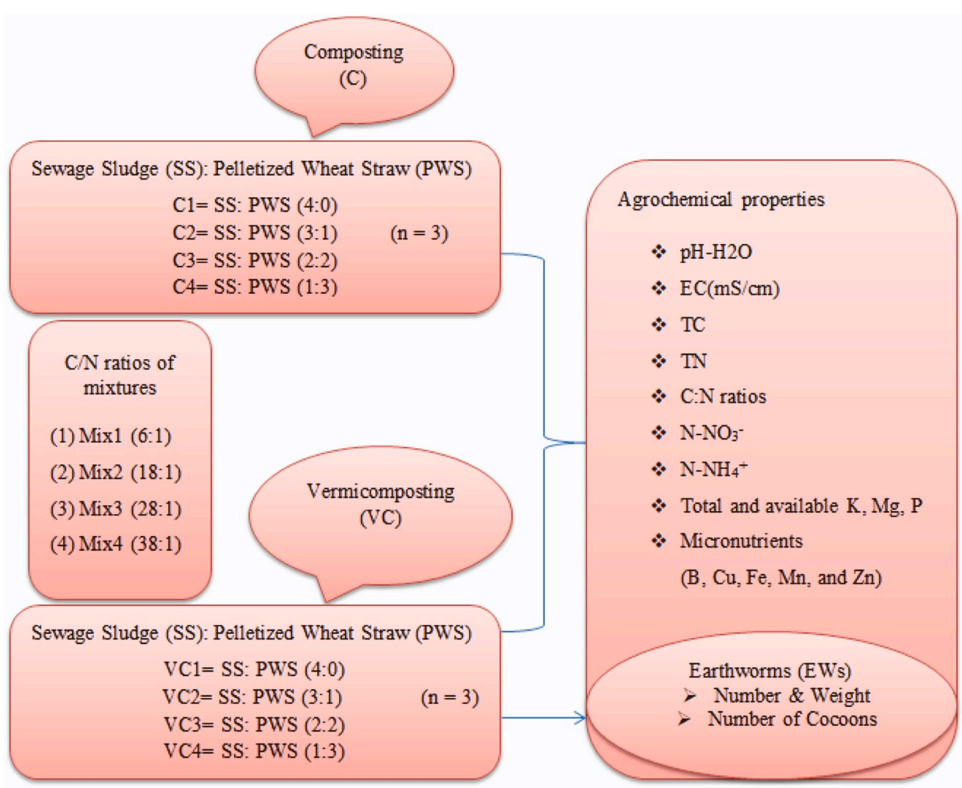


**Fig. 1.** The experimental study design.

### 2.4. Statistical analyses

The Shapiro-Wilk and Bartlett tests were used to ensure that the data were normal and homogeneous. The residual plot points were normally distributed around the mean with relatively homogeneous variances matching the variance analysis hypotheses. Two-way ANOVA was used to analyse the variation of agrochemical properties and determine significant differences in the properties of the final product between composting methods and C/N ratios. Post-hoc analysis was performed to determine significant differences using Tukey's test on the mean values. The statistical analyses used R version 4.0.2 and Statistica 12 software (StatSoft, Tulsa, USA). The level of the statistical test for significance was set at $p < 0.05$.

## 3. Results and discussion

### 3.1. Changes in temperature during vermicomposting and composting

The temperature during vermicomposting ranged from 19° to 28°C (Fig. 2a), which was lower than during composting and better for earthworms (Sinha et al., 2002). The temperature of the variant with a 38:1 C/N ratio (VC4) increased to 28.6 °C at the start (day one) of vermicomposting. During days three and two, the temperatures of (C3) and (C4) rapidly reached the thermophilic stage (>45 °C) (Fig. 2b). In four days, C4 reached a maximum thermophilic phase reading of 65.5 °C, while C3 reached 57.4 °C. The thermophilic phase lasted 14 days in variant C4 and ten days in C3.

The maximum temperatures lasted seven days for variant C2 (37.6 °C) and eight days for variant C1 (29.6 °C), the temperatures then gradually dropped over the remainder of the experimental period. The highest C/N ratio caused the most rapid thermophilic decomposition during the first 10–14 days. However, because of the depletion of easily degraded organic compounds, the degradation process resulted in less heat in these mixtures during the cooling phase (Wu et al., 2017). The variants with C/N ratios of 6:1(C1) and 18:1 (C2) reached maturity at mesophilic temperatures. These results might have stemmed from the high moisture content (79–84%) in these variants or because the SS: PWS ratio affected microbial activity, which influenced the temperature distribution of the composting process. After 60 days of composting, all variants' temperatures were near ambient and constant (Fig. 2b).

### 3.2. pH and electrical conductivity (EC)

The changes in pH and EC of the variants during composting and vermicomposting are shown in Fig. 3. Vermicomposting and composting showed significantly different trends in pH among the variants in each time period (Fig. 3). The pH significantly ($p < 0.001$) decreased during vermicomposting. For example, variant VC2 showed a significant reduction in pH from 7.3 to 5.2 (Fig. 3a), most likely caused by the transformation of organic phosphorus into orthophosphates, and the conversion of biomass into organic acids as humic substances during vermicomposting (Lazcano et al., 2008; Sharma and Garg, 2018; Suthar, 2010). During composting, the variants showed significant ($p < 0.05$) differences in pH with the values decreasing up to 90 days and then gradually increasing up to 120 days (Fig. 3b).

The highest pH value occurred in variant C1, which increased from an initial value of 6.9–8.6 during composting. According to Gigliotti et al. (2012), microorganisms break down organic nitrogen-containing compounds such as proteins to ammonia ($NH_3$). Ammonia is alkaline and elevates the pH of the compost. The final pH value of the compost was significantly higher than that of vermicompost. Several researchers have reported similar pH changes during the composting and vermicomposting of SS, crop straw, municipal solid waste, and livestock manure (Li et al., 2012; Singh and Suthar, 2012; Wang et al., 2014). According to Singh and Suthar (2012), the pH differences among variants could indicate the degree of organic material mineralization.

The EC increased significantly during vermicomposting and composting ($p < 0.001$); however, the final EC of the vermicompost (Fig. 3**c**) was significantly higher than that of compost (Fig. 3d). The variant with the highest C/N ratio (38:1) exhibited the highest EC value during vermicomposting. The production of inorganic ions and dissolved substances such as phosphate, ammonium, and nitrate could have contributed to the increase in EC in vermicompost (Lazcano et al., 2008; He et al., 2016; Negi and Suthar, 2018), and this occurrence indicated that vermicomposting might increase the mineralization of organic matter by transforming insoluble materials to soluble materials. At the end of composting, the values of EC ranged from 0.68 to 2.14 mS/cm, while for vermicomposting the values varied from 2.10 to 2.28 mS/cm. Thus, in both vermicompost and compost, all variants' EC values were within the recommended limit (4 mS/cm) (Li et al., 2012).

### 3.3. Total carbon(TC), total nitrogen(TN) and C/N ratio

The TC, TN, and C/N values changed significantly ($p < 0.001$) over the period of vermicomposting and composting (Fig. 4). Compared to the initial level, the TC decreased in all variants during vermicomposting (Fig. 4a) and composting (Fig. 4b), and the final TC in vermicompost was lower than that of compost in all variants.

The TC in vermicompost, VC1, VC2, VC3, and VC4, over the period of 120 days was 27.6%, 22.6%, 18.5%, and 16%, respectively. In compost, C1, C2, C3, and C4, the TC was 24.2%, 17.5%, 17.7%, and 11.9%, respectively. The most significant reduction in TC was recorded in the variant VC1 with a 6:1 C/N ratio during vermicomposting, followed by variant VC2 with an 18:1 C/N ratio. Microbial respiration and earthworm activity during vermicomposting reduce TC (Garg et al., 2006; Hanc et al., 2017). Rini et al. (2020) found a decrease in TC during vermicomposting of solid livestock wastes with earthworms of the species *Perionyx excavatus and Eudrilus eugeniae* for two cycles, 45 days and 90 days. Esmaeili et al. (2020) also showed a decrease in TC during vermicomposting pistachio waste mixed with cow dung in various ratios

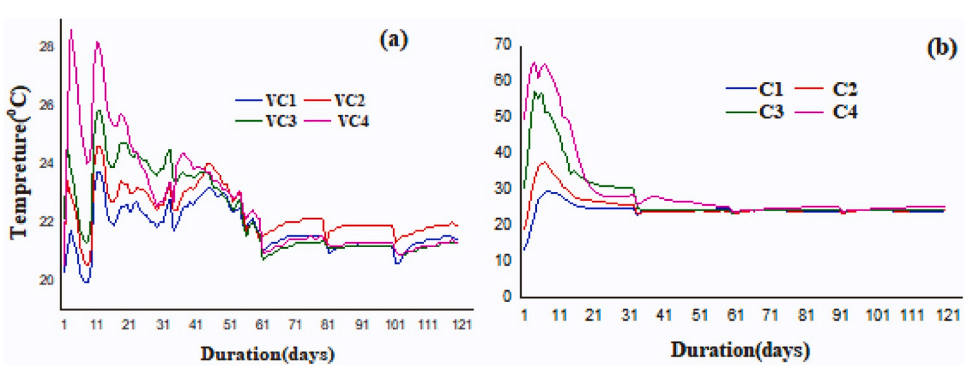


**Fig. 2.** Temperature variations during (**a**) vermicomposting and (**b**) composting.

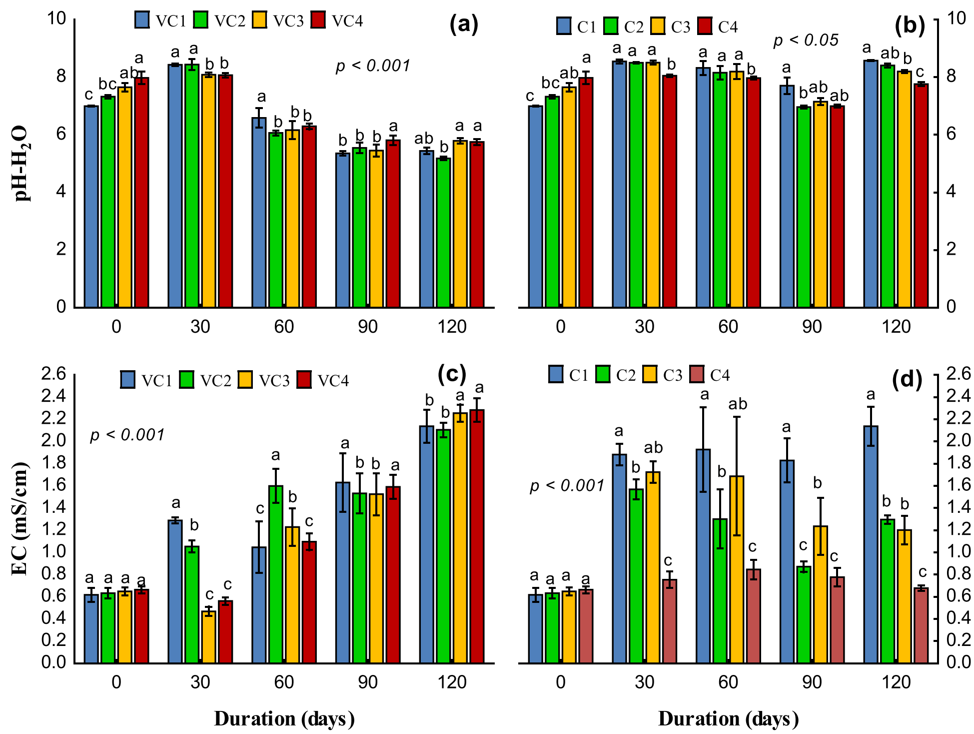


**Fig. 3.** Changes in pH and EC in variants during vermicomposting and composting. The bars represent the standard error of the mean (n = 3). Different letters indicate significant differences among the variants ($p < 0.05$) in each time period.

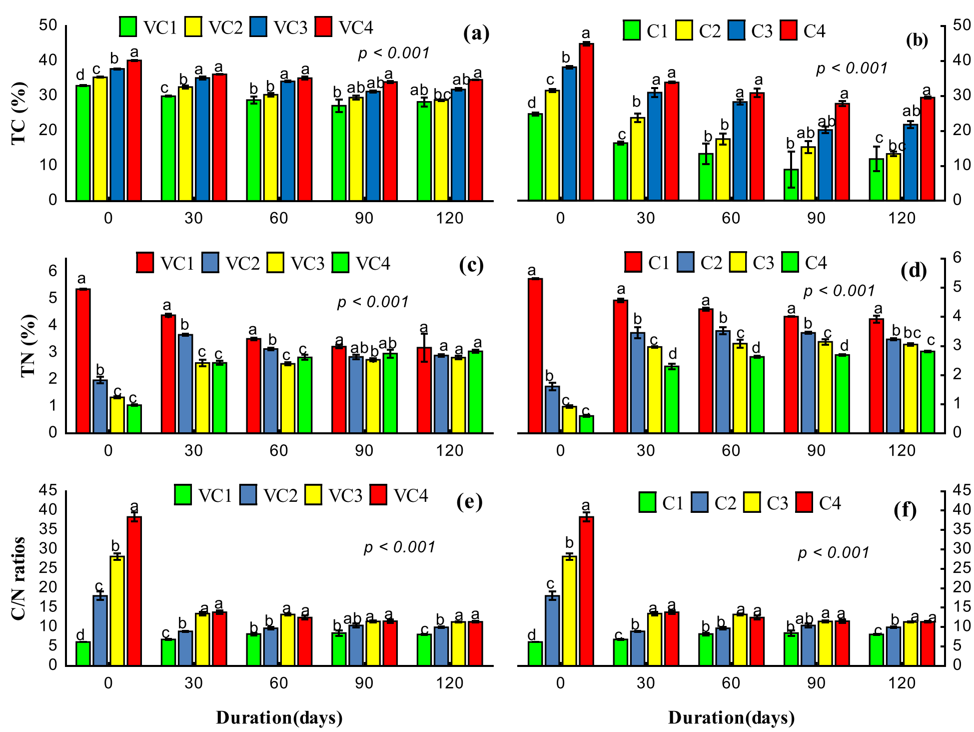


**Fig. 4.** TC, TN, and C/N in variants during of vermicomposting and composting. Bars indicate standard error of the mean (n = 3). Different letters indicate significant differences among the variants ($p < 0.05$) in each time period.

for 45 days using *Eisenia fetida*. Microbes use carbon to produce energy for metabolism (Esmaeili et al., 2020; Ravindran et al., 2015; Arumugam et al., 2018). The observed reduction in TC revealed that organic compounds were being bio-degraded and mineralized as a result of microbial activity in the variants, resulting in the release of carbon dioxide (Khatua et al., 2018; Yang et al., 2017).

TN increased in all variants during vermicomposting (Fig. 4c) and composting (Fig. 4d) from the initial values, except in the variant VC1 with a 6:1 C/N ratio. However, the final TN in vermicompost was lower than in compost in all variants. In the final (120 days) vermicompost, the increase in TN in variants VC2, VC3, and VC4 reached 31.5%, 52.5%, and 65.6%, respectively, while in C2, C3, and C4 it reached 43.4%, 59.4%, and 66.1%, respectively. The reduction in TN was 68% in VC1 and 30.7% in C1 after 120 days. Pigatin et al. (2016) found that by using *E. foetida* for vermicomposting, the TN in agricultural residues increased from 19.5% to 152% in 60 days. Dume et al. (2022) reported that vermicomposting hydrolysed chicken feather residue for 120 days using *Eisenia andrei* earthworms increased TN content by 42.3–56.86%, compared to 56.4–61.4% during composting (without earthworms). Kaushik and Garg (2004) also reported that 11 weeks of vermicomposting using *E. foetida* with sludge from textile mills mixed with cow dung and agricultural waste increased nitrogen levels 2–3 times over the initial feedstocks. Sudkolai and Nourbakhsh (2017) found that after 60 days of vermicomposting with *E. foetida*, wheat residue vermicompost had 3.2 times the TN content of the initial feedstocks. The increase in TN levels in vermicompost is most likely due to the addition of organic carbon from $CO_2$ and nitrogen from earthworms' nitrogenous excretory substances in the form of mucus and growth-stimulating hormones.

The C/N ratio decreased during vermicomposting (Fig. 4e) and composting (Fig. 4f). The reduction in C/N ratio in vermicompost, VC2, VC3, and VC4, reached 81%, 148.9%, 238.3%, respectively, and in compost, C2, C3, C4, 107.2%, 190.4%, and 227.9%, respectively. Because it reflected the rates of stabilization and mineralization, the C/N ratio indicated vermicompost maturity (Arumugam et al., 2018; Srivastava et al., 2020; Soobhany et al., 2015). Over time, the decrease in the C/N ratio was correlated with enhanced nitrogen content and organic matter degradation (Devi and Khwairakpam, 2020a). Previous research by Karmegam et al. (2019) and Biruntha et al. (2020) supported these findings, reporting up to a 50.9% and a 48.8% reduction in the C/N ratio during vermicomposting of cow dung and cow dung with vegetable waste, respectively. Zhi-wei et al. (2019) reported that feeding rice straw and kitchen waste to *Eisenia fetida* for 45 days decreased the C/N ratio by 58.55–71.96%. Boruah et al. (2019) also found the C/N ratio was reduced by 91.10% during the vermicomposting of citronella bagasse and paper mill sludge by *E. fetida* for 45 days. The final C/N ratios recorded for all the variants were within the recommended value (<20) for soil applications (Esmaeili et al., 2020).

### 3.4. Mineral Nitrogen (N-$NO_3^-$ and N-$NH_4^+$)

Fig. 5 shows the content of nitrate nitrogen (N-$NO_3^-$) and ammonium nitrogen (N-$NH_4^+$). The N-$NO_3^-$ content during vermicomposting (Fig. 5a) and composting (Fig. 5b) increased in all variants. The final N-$NO_3^-$ content with respect to the initial value, in vermicompost showed an overall increase of 99.96% (VC1), 99.89% (VC2), 99.80% (VC3), and 99.70% (VC4); in compost, the increase was 98.96% (C1), 97.15% (C2), 91.3% (C3), and 98.97% (C4). The final N-$NH_4^+$ content in vermicompost decreased in VC1 and VC2, but increased in VC3 and VC4 (Fig. 5c). In compost, the final N-$NH_4^+$ content increased by 70.4% (C1), 67.2% (C2), 72.4% (C3), and 15% (C4) (Fig. 5d). The increase in N-$NO_3^-$ levels during vermicomposting was consistent with the findings of Hait and Tare (2012), who showed a decrease in N-$NH_4^+$ and an increase in N-$NO_3^-$ during SS vermicomposting versus composting. During the nitrification process, a significant proportion of N-$NH_4^+$ can be transformed into N-$NO_3^-$, and a portion of N-$NH_4^+$ can also be vaporised as $NH_3$.

There is also the potential for nitrogen loss due to N-$NO_3^-$ being converted into $N_2$ during denitrification (Van Vliet et al., 2004). Tognetti et al. (2007) claimed that the decline of N-$NH_4^+$ implied compost maturity, and Wu et al. (2017) also reported a similar trend of N-$NH_4^+$ and N-$NO_3^-$ changes that occurred during the composting of pig manure. N-$NH_4^+$ was reduced during the decomposition of organic matter due to nitrogen fixation, ammonia volatilization, and immobilisation by microbes (Raj and Antil, 2011; Van Vliet et al., 2004; Awasthi et al., 2016). The reduction of $NH_4^+$ in vermicompost indicated maturity of the final vermicompost product.

### 3.5. Total and available contents of K, Mg and P macronutrients

The total content of K, Mg and P was significantly ($p < 0.001$) increased during vermicomposting and composting (Fig. 6). The final total K level increased significantly among the variants, with an overall increase of 56%, 57%, 63%, and 73% in vermicompost for VC1, VC2, VC3, and VC4, respectively (Fig. 6a) and 18%, 34%, 49%, and 56% in compost for C1, C2, C3, and C4, respectively (Fig. 6b). The percentage of

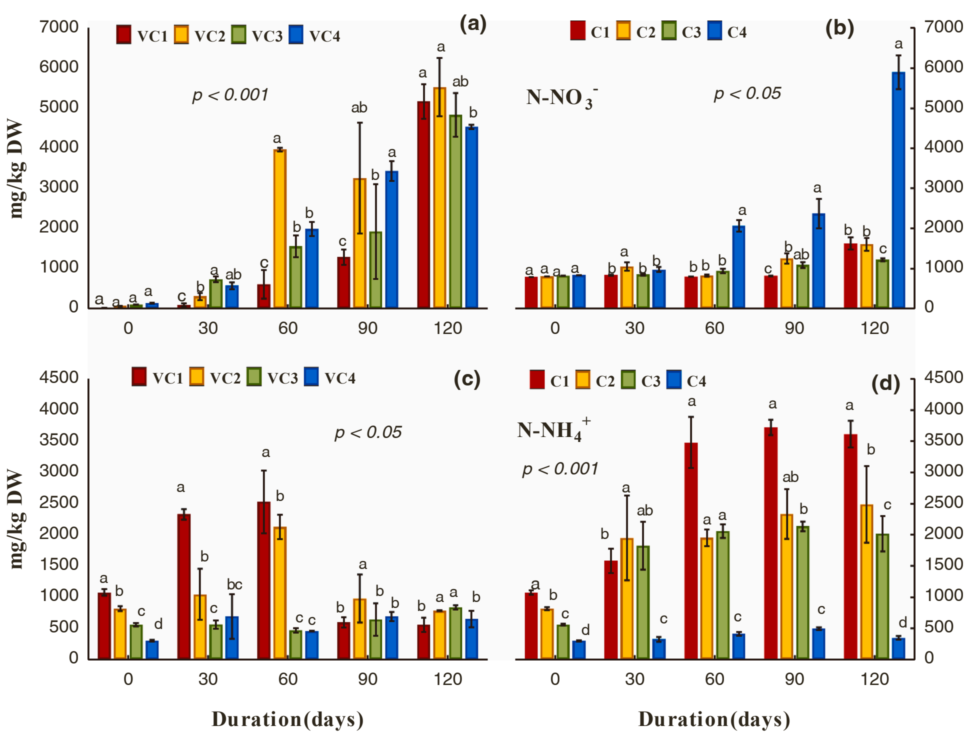


**Fig. 5.** Mineral nitrogen (N-$NO_3^-$ and N-$NH_4^+$) in variants during vermicomposting and composting. Bars indicate the standard error of the mean (n = 3). Different letters indicate significant differences among the variants ($p < 0.05$) in each time period.

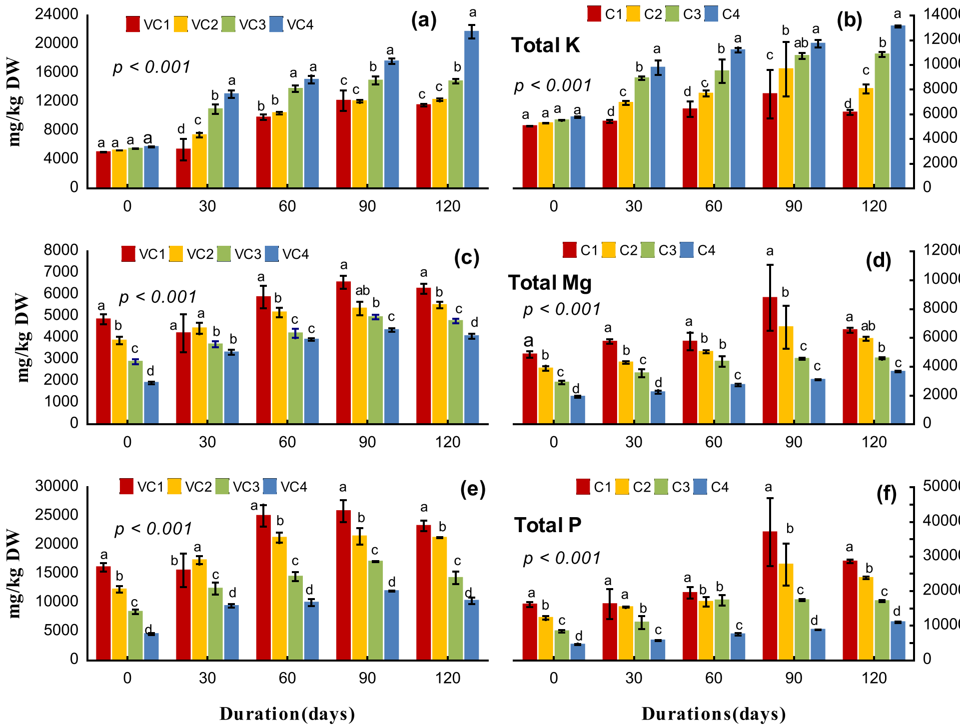


**Fig. 6.** Total K, Mg, and P macronutrients in variants during vermicomposting and composting. Bars indicate the standard error of the mean (n = 3). Different letters indicate significant differences among the variants ($p < 0.05$) in each time period.

total K in vermicompost was 37–88% higher than in compost. Total Mg significantly increased with overall changes of 23%, 30%, 39%, and 53% in vermicompost (Fig. 6c) for VC1, VC2, VC3, and VC4, respectively, and 26%, 35%, 37%, and 47% in compost (Fig. 6d) for C1, C2, C3, and C4, respectively. However, vermicompost showed significant increases of total Mg in the variants with 28:1 and 38:1 C/N ratios by 4% and 12% over compost. The total P increased significantly with overall increases of 31%, 42%, 41%, and 56% for VC1, VC2, VC3, and VC4, respectively (Fig. 6e), and 43%, 48%, 51%, and 59% in compost C1, C2, C3, and C4, respectively (Fig. 6f).

The concentration of plant-available K, Mg, and P increased during vermicomposting and composting (Fig. 7), with significant ($p < 0.001$)

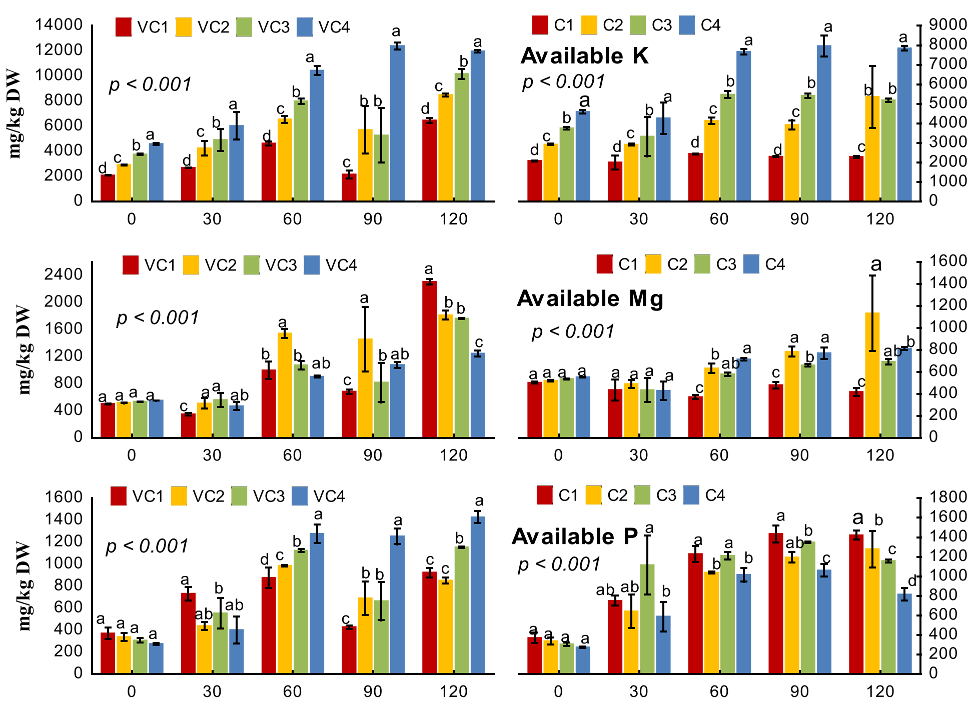


**Fig. 7.** Available K, Mg, and P macronutrients in variants during vermicomposting and composting. Bars indicate standard error of the mean (n = 3). Different letters indicate significant differences among the variants ($p < 0.05$) in each time period.

differences during vermicomposting. The available K in vermicompost increased significantly among the variants, with overall increases of 68%, 66%, 63%, and 62% in VC1, VC2, VC3, and VC4, respectively (Figs. 7a), and9%, 45%, 28%, and 42% in compost for C1, C2, C3, and C4, respectively (Fig. 7b); the percentage of available K in vermicompost increased by 53–183% over compost.

The overall increase in available Mg in vermicompost was 78%, 71%, 70%, and 56% for VC1, VC2, VC3, and VC4, respectively (Figs. 7c), and 3%, 54%, 23%, and 32% in compost for C1, C2, C3, and C4, respectively (Fig. 7d), and the percentage of available Mg in vermicompost over compost increased from 54% to 453%. Available P rose sharply among the variants overall increases of 60%, 60%, 73%, and 81% in vermicompost for VC1, VC2, VC3, and VC4, respectively (Fig. 7e), and 74%, 73%, 74%, and 66% in compost for C1, C2, C3, and C4, respectively (Fig. 7f). Vermicompost with 38:1 C/N showed a significant increase of 79% in available P over compost.

The changes in K, Mg, and P were probably due to the high mass loss under vermicomposting. There was no additional nutrient input unless the worms died and decomposed during vermicomposting. An increase in these macronutrients has been linked to decrease in weight and organic matter (Wani and Rao, 2013). The increase in potassium might be related to acid production by microbes, which causes the solubilization of organically bound potassium (Garg et al., 2006), and also an earthworm's intestine may aid in the release of K in vermicompost (Khatua et al., 2018; Pramanik et al., 2007). These influences could have resulted in an overall rise in total K in the variants. An earthworm's gut can increase the release of potassium in vermicompost (Pramanik et al., 2007; Khatua et al., 2018). These influences could all have contributed to the variants' overall potassium rise over time. The existence of phosphatase in earthworm intestine that enhance P release in various forms and phosphorus-solubilizing microbes in their casts may explain the rise in phosphorus, (Deka et al., 2011). The mineralization and mobilization of organic matter by earthworms, and the combined effect of microorganisms and phosphate excretion may also have increased P content (Yadav and Garg, 2019). The reduction in pH could also have enhanced the solubilization of phosphorous and the release of organically bound phosphate, thus increasing its concentration in the final product (Devi and Khwairakpam, 2020a; b). Ghosh et al. (2018) found phytase enzymes that enhance phosphorus mineralization.

### 3.6. *Availability of micronutrients, B, Cu, Fe, Mn, and Zn*

Fig. 8 depicts the available B, Cu, Fe, Mn, and Zn contents during vermicomposting and composting. The availability of these nutrients increased significantly ($p < 0.001$) in all vermicomposting and composting variants compared to initial concentrations. The B content in vermicompost increased significantly among the variants, with overall increases of 80%, 78%, 82%, and 82% in vermicompost for VC1, VC2, VC3, and VC4, respectively (Fig. 8a), and 21%, 67%, 60%, and 65% in compost for C1, C2, C3, and C4, respectively (Fig. 8b), and the available B in vermicompost increased significantly from 48% to 303% over compost. The content of available Cu in vermicompost increased significantly from 2.5% to 82% over compost (Fig. 8c). The available Fe was significantly elevated in vermicompost with overall increases of 8%, 25%, 48%, and 66% for VC1, VC2, VC3, and VC4, respectively (Fig. 8e), and 55%, 59%, 49%, and 75% in compost for C1, C2, C3, and C4, respectively (Fig. 8f). The lower Fe contents found in vermicompost over compost may be due to the bioaccumulation of Fe in earthworm tissues (Suthar and Gairola, 2014). The final results of available Mn in compost showed an overall increase of 41%, 39%, and 49% for C2, C3, and C4, respectively (Fig. 8h), and a 56% decrease in C1, whereas in vermicompost, Mn decreased by 3%, 7%, 11%, and 27% in VC1, VC2, VC3, and VC4, respectively (Fig. 8g). Available Zn increased significantly among the variants with overall increases of 47%, 78%, 78%, and 81% for C1, C2, C3, and C4, respectively (Fig. 8j), and 60%, 68%, 72%, and 79% in vermicompost for VC1, VC2, VC3, and VC4, respectively (Fig. 8i).

The increases in these nutrients are caused by the earthworm's

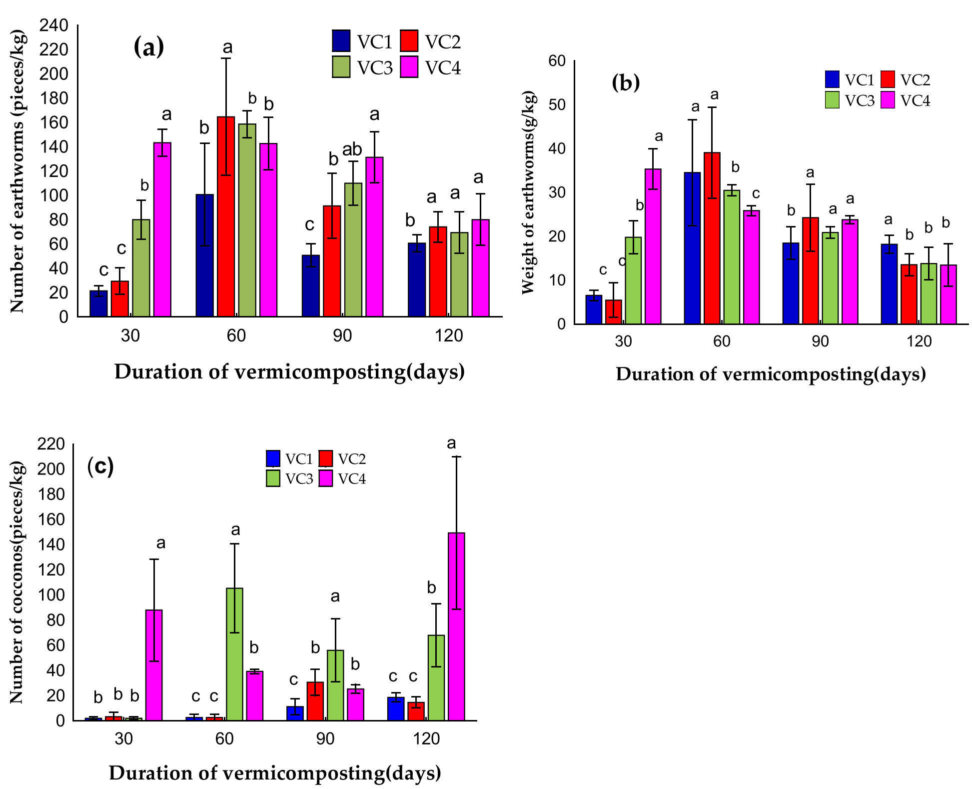


**Fig. 9.** Number (**a**) and weight (**b**) of earthworms and number of cocoons (**c**) during vermicomposting. Bars indicate standard error of the mean (n = 3). Different letters indicate significant differences among the variants ($p < 0.05$) in each time period.

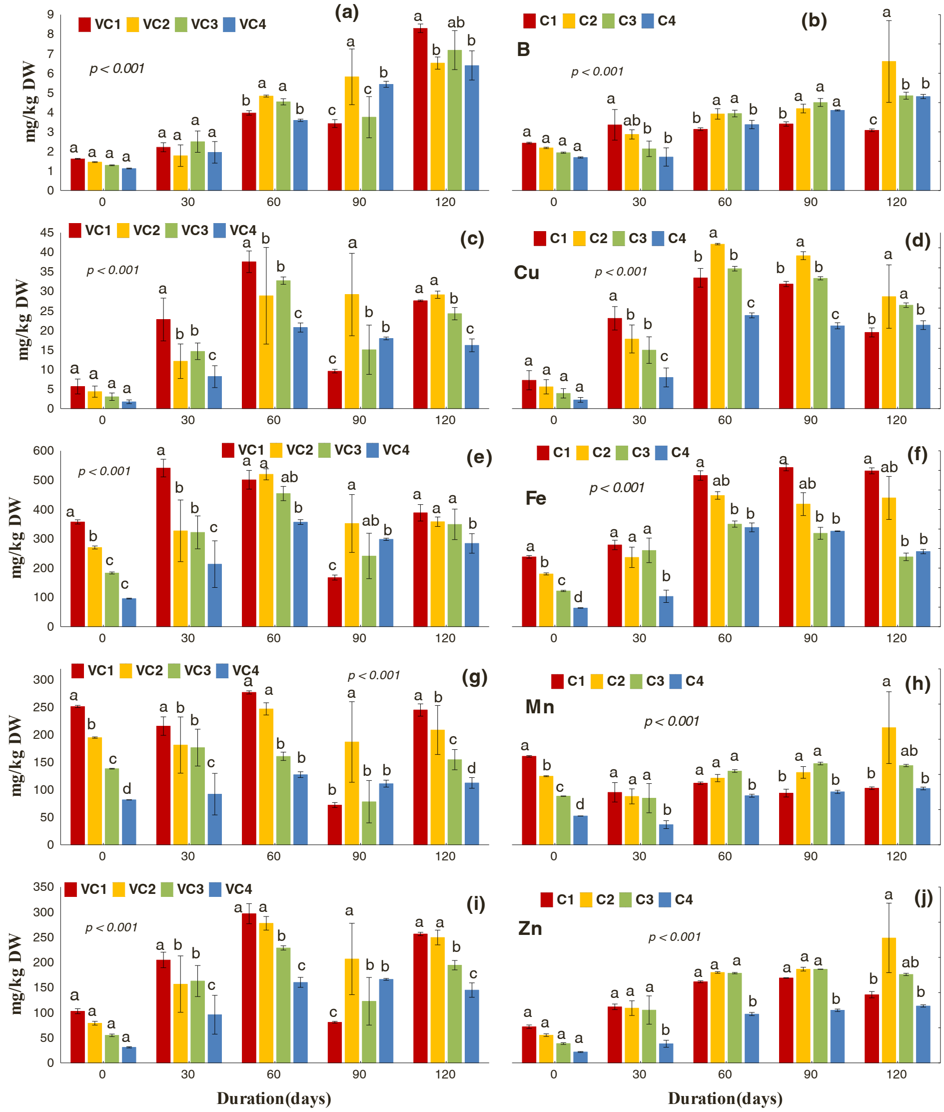


**Fig. 8.** Available B, Cu, Fe, Mn, Zn micronutrients in variants during vermicomposting and composting. Bars indicate standard error of the mean (n = 3). Different letters indicate significant differences among the variants ($p < 0.05$) in each time period.

catabolic activity on carbonic anhydrase in the calciferous gland and the accumulation of Zn in their tissues during vermicomposting (Gupta and Garg, 2008; Manyuchi and Phiri, 2013; El-Haddad et al., 2014). Our results are consistent with those of Gupta and Garg (2008), who found higher concentrations of micronutrients in sewage sludge vermicompost, and the increase in available micronutrient concentrations could be attributed to the progressive mineralization of organic matter and loss through respiration during the composting process (Amir et al., 2005; Lv et al., 2016). Our increases in B, Cu, Fe, Mn, and Zn followed the same pattern as those of Pattnaik and Reddy (2010) and Dortzbach (2010) reported that pig manure strongly enhanced Mn, Cu, and Zn concentrations.

### 3.7. Growth and reproduction of earthworms (E. andrei)

Fig. 9 depicts the number and weight of earthworms and the number of cocoons. The average initial earthworm weight and number were 0.2 g/piece and 125 pieces per kg of substrate.

The initial weight of earthworms was 25 g per kg of substrate. Earthworm production was very low during the first 30 days in the variants with 6:1 and 18:1 C/N ratios relative to the variants with 28:1 and 38:1 C/N ratios. The maximum number (Fig. 9a), 165 pieces/kg, and weight (Fig. 9b), 39 g/kg, were recorded in the variant with an 18:1 C/N ratio after 60 days of vermicomposting, while the lowest number, 21pieces/kg, occurred in the 6:1 C/N variant after 30 days of vermicomposting (Fig. 9c). Cocoon production was very low during the first 30 days except in the 38:1 C/N group. After 120 days, the 38:1 C/N variant had the highest number of cocoons (150 pieces/kg), while the variant with a 28:1 C/N ratio had the lowest (15 pieces/kg). Cocoon production fluctuated during the vermicomposting period. The cocoon production rate was initially low, but increased with vermicomposting time. The C/N ratio, a vital determinant of earthworm production, could explain differences in cocoon production among the variants. A high C/N ratio promotes growth and reproduction by providing earthworms with greater amounts of organic matter (Gupta et al., 2007).

## 4. Conclusions

This research highlights the crucial role of carbon-to-nitrogen (C/N) ratios and the composting and vermicomposting processes in determining the characteristics of the final products. Our findings show that both composting and vermicomposting were feasible at a range of C/N ratios, although variations were observed in the final product quality. However, a comparison between the two end-products derived from the same initial materials (sewage sludge and pelletized wheat straw) revealed that vermicomposting led to increased electrical conductivity (EC), total and available potassium (K), available magnesium (Mg), total Mg, available phosphorus (P), nitrate nitrogen ($N\text{-}NO_3^-$), available boron (B), and copper (Cu). However, vermicomposting resulted in decreases in pH, total carbon (TC) and total nitrogen (TN), available iron (Fe), manganese (Mn), zinc (Zn), and ammonium ($NH_4^+$). The highest number of earthworms was recorded in the variant with an 18:1 C/N ratio after 60 days of vermicomposting, while the lowest number was observed in the variant with a 6:1 C/N ratio after 30 days of vermicomposting. The agrochemical characteristics of the 18:1 C/N ratio vermicompost significantly outperformed those of compost; therefore, vermicomposting demonstrated superior agrochemical properties compared to composting. This study confirmed that vermicomposting sewage sludge mixed with pelletized wheat straw at an 18:1 C/N ratio yielded the best results, likely due to improved and favourable agrochemical properties.

## CRediT authorship contribution statement

**Bayu Dume:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Ales Hanc**: Conceptualization, Formal analysis, Resources, Data curation, Writing – original draft, Methodology, Supervision, Project administration, Funding acquisition. **Pavel Svehla:** Conceptualization, Methodology, Supervision, Formal analysis, Resources, Data curation, Writing – original draft. **Pavel Michal, Abraham Demelash Chane:** Sample, Data collection. **Abebe Nigussie**: Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

## Acknowledgements

Financial support for this work was provided by the Ministry of Agriculture of the Czech Republic under the NAZV project number QK1910095. The authors would like to thank Proof-Reading-Service.com for professionally proofreading the English text.

## References

Akratos, C.S., Tekerlekopoulou, A.G., Vasiliadou, I.A., and Vayenas, D.V., 2017. Co-composting of olive mill waste for the production of soil amendments. In Olive Mill Waste 161–182. Academic Press.
Alvarenga, P., Mourinha, C., Farto, M., Santos, T., Palma, P., Sengo, J., Cunha-Queda, C., 2015. Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: benefits versus limiting factors. Waste Manag. 40, 44–52.
Amir, S., Hafidi, M., Merlina, G., Revel, J.C., 2005. Sequential extraction of heavy metals during composting of sewage sludge. Chemosphere 59, 801–810.
Arumugam, K., Renganathan, S., Babalola, O.O., Muthunarayanan, V., 2018. Investigation on paper cup waste degradation by bacterial consortium and *Eudrillus eugeinea* through vermicomposting. Waste Manag. 74, 185–193.
Awasthi, M.K., Pandey, A.K., Bundela, P.S., Wong, J.W., Li, R., Zhang, Z., 2016. Co-composting of gelatin industry sludge combined with organic fraction of municipal solid waste and poultry waste employing zeolite mixed with enriched nitrifying bacterial consortium. Bioresour. Technol. 213, 181–189.
Awiszus, S., Meissner, K., Reyer, S., Müller, J., 2018. Ammonia and methane emissions during drying of dewatered biogas digestate in a two-belt conveyor dryer. Bioresour. Technol. 247, 419–425.
Bernal, M.P., Alburquerque, J.A., Moral, R., 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. Bioresour. Technol. 100, 5444–5453.
Biruntha, M., Karmegam, N., Jeyaprakasam, A., Selvi, B.K., Paul, J.A.J., Balamurali krishnan, B., Chang, S.W., Ravindran, B., 2020. Vermiconversion of biowastes with low-to-high C/N ratio into value added vermicompost. Bioresour. Technol. 297, 122398.
Boruah, T., Barman, A., Kalita, P., Lahkar, J., Deka, H., 2019. Vermicomposting of citronella bagasse and paper mill sludge mixture employing *Eisenia fetida*. Bioresour. Technol. 294, 122147.
BSI EN 13651, 2001. Soil Improvers and Growing Media - Extraction of Calcium Chloride/ DTPA (CAT) Soluble Nutrients.
BSI EN 15933, 2012. Sludge, Treated Biowaste and Soil Determination of pH.
Deka, H., Deka, S., Baruah, C.K., Das, J., Hoque, S., Sarma, H., Sarma, N.S., 2011. Vermicomposting potentiality of Perionyx excavatus for recycling of waste biomass of java citronella - an aromatic oil yielding plant. Bioresour. Technol. 102, 11212–11217.
Devi, C., Khwairakpam, M., 2020a. Bioconversion of Lantana camara by vermicomposting with two different earthworm species in monoculture. Bioresour. Technol. 296, 122308.
Devi, C., Khwairakpam, M., 2020b. Management of lignocellulosic green waste Saccharum spontaneum through vermicomposting with cow dung. Waste Manag. 113, 88–95.
Dortzbach, A.D., 2010. Accumulation of zinc, copper and manganese in soil fertilized with pig manure and urea in Southern State of Santa Catarina (Brazil). In 19th World Congress of Soil Science, Soil Solutions for a Changing World Brisbane, Australia.
Dume, B., Hanc, A., Svehla, P., Michal, P., Solcova, O., Chane, A.D., Nigussie, A., 2022. Nutrient recovery and changes in enzyme activity during vermicomposting of hydrolysed chicken feather residue. Environ. Technol. 43, 1–27.
El-Haddad, M.E., Zayed, M.S., El-Sayed, G.A.M., Hassanein, M.K., El-Satar, A.M.A., 2014. Evaluation of compost, vermicompost and their teas produced from rice straw as affected by addition of different supplements. Ann. Agric. Sci. 59, 243–251.
El-mrini, S., Aboutayeb, R., Zouhri, A., 2022. Effect of initial C/N ratio and turning frequency on quality of final compost of turkey manure and olive pomace. J. Eng. Appl. Sci. 69 (1), 1–20.
Esmaeili, A., Khoram, M.R., Gholami, M., Eslami, H., 2020. Pistachio waste management using combined composting-vermicomposting technique: physico-chemical changes and worm growth analysis. J. Clean. Prod. 242, 118523.
FAO., 2017. Small-scale vermicomposting: A guide to vermicomposting at home for poverty reduction and sustainable development. Retrieved from ⟨http://www.fao.org/3/a-i6932e.pdf⟩.
Fornes, F., Mendoza-Hernández, D., García-de-la-Fuente, R., Abad, M., Belda, R.M., 2012. Composting versus vermicomposting: a comparative study of organic matter evolution through straight and combined processes. Bioresour. Technol. 118, 296–305.
García-Gómez, C., Fernández, M.D., Babin, M., 2014. Ecotoxicological evaluation of sewage sludge contaminated with zinc oxide nanoparticles. Arch. Environ. Contam. Toxicol. 67, 494–506.
Garg, P., Gupta, A., Satya, S., 2006. Vermicomposting of different types of waste using Eisenia foetida: a comparative study. Bioresour. Technol. 97, 391–395.
Ghosh, S., Jyoti, A., Kumar, G., Pramanik, P., 2018. Quantifying the relative role of phytase and phosphatase enzymes in phosphorus mineralization during vermicomposting of fi brous tea factory waste. Ecol. Eng. 116, 97–103.
Gigliotti, G., Proietti, P., Said-Pullicino, D., Nasini, L., Pezzolla, D., Rosati, L., Porceddu, P.R., 2012. Co-composting of olive husks with high moisture contents: organic matter dynamics and compost quality. Int. Biodeter. Biodegr. 67, 8–14.
Guilayn, F., Jimenez, J., Martel, J.-L., Rouez, M., Crest, M., Patureaua, D., 2019. First fertilizing-value typology of digestates: a decision-making tool for regulation. Waste Manag. 86, 67–79.
Guo, R., Li, G., Jiang, T., Schuchardt, F., Chen, T., Zhao, Y., Shen, Y., 2012. Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. Bioresour. Technol. 112, 171–178.
Gupta, R., Garg, V.K., 2008. Stabilization of primary sludge during vermicomposting. J. Hazard. Mater. 153, 1023–1030.
Gupta, R., Garg, V.K., 2011. Potential and possibilities of vermicomposting in sustainable solid waste management: a review. Int. J. Environ. Waste Manag. 7 (3–4), 210–234.
Gupta, R., Mutiyar, P.K., Rawat, N.K., Saini, M.S., Garg, V.K., 2007. Development of a water hyacinth based vermireactor using an epigeic earthworm E. foetida. Bioresour. Technol. 98, 2605–2610.
Hait, S., Tare, V., 2012. Transformation and availability of nutrients and heavy metals during integrated composting–vermicomposting of sewage sludge. Ecotoxicol. Environ. Saf. 79, 214–224.
Hanc, A., Dreslova, M., 2016. Effect of composting and vermicomposting on properties of particle size fractions. Bioresour. Technol. 217, 186–189.
Hanc, A., Szakova, J., Svehla, P., 2012. Effect of composting on the mobility of arsenic, chromium and nickel contained in kitchen and garden waste. Bioresour. Technol. 126, 444–452.
Hanc, A., Častková, T., Kužel, S., Cajthaml, T., 2017. Dynamics of a vertical-flow windrow vermicomposting system. Waste Manag. Res. 35, 1121–1128.
Hanc, A., Dume, B., Hrebeckova, T., 2022. Differences of enzymatic activity during composting and vermicomposting of sewage sludge mixed with straw pellets. Front. Microbiol. 12, 3892.
He, X., Zhang, Y., Shen, M., Zeng, G., Zhou, M., Li, M., 2016. Effect of vermicomposting on concentration and speciation of heavy metals in sewage sludge with additive materials. Bioresour. Technol. 218, 867–873.
Huang, G.F., Wong, J.W.C., Wu, Q.T., Nagar, B.B., 2004. Effect of C/N on composting of pig manure with sawdust. Waste Manag. 24, 805–813.
Karmegam, N., Vijayan, P., Prakash, M., John Paul, J.A., 2019. Vermicomposting of paper industry sludge with cow dung and green manure plants using *Eisenia fetida*: a

viable option for cleaner and enriched vermicompost production. J. Clean. Prod. 228, 718–728.
Karwal, M., Kaushik, A., 2020. Co-composting and vermicomposting of coal fly-ash with press mud: changes in nutrients, micro-nutrients and enzyme activities. Environ. Technol. Innov., 102529
Kaushik, P., Garg, V.K., 2003. Vermicomposting of mixed soil textile mill sludge and cow dung with the epigeic earthworm *Eisenia foetida*. Bioresour. Technol. 90, 311–316.
Kaushik, P., Garg, V.K., 2004. Dynamics of biological and chemical parameters during vermicomposting of solid textile mill sludge mixed with cow dung and agricultural residues. Bioresour. Technol. 94, 203–209.
Khatua, C., Sengupta, S., Balla, V.K., Kundu, B., Chakraborti, A., Tripathi, S., 2018. Dynamics of organic matter decomposition during vermicomposting of banana stem waste using *Eisenia fetida*. Waste Manag. 79, 287–295.
Kinney, C.A., Campbell, B.R., Thompson, R., Furlong, E.T., Kolpin, D.W., Burkhardt, M. R., Zaugg, S.D., Werner, S.L., Hay, A.G., 2012. Earthworm bioassays and seedling emergence for monitoring toxicity, aging and bioaccumulation of anthropogenic waste indicator compounds in biosolids-amended soil. Sci. Total Environ. 433, 507–515.
Kumar, M., Ou, Y.L., Lin, J.G., 2010. Co-composting of green waste and food waste at low C/N ratio. Waste Manag. 30, 602–609.
Lazcano, C., Gómez-Brandón, M., Domínguez, J., 2008. Comparison of the effectiveness of composting and vermicomposting for the biological stabilization of cattle manure. Chemosphere 72, 1013–1019.
Li, R., Wang, J.J., Zhang, Z., Shen, F., Zhang, G., Qin, R., Li, X., Xiao, R., 2012. Nutrient transformations during composting of pig manure with bentonite. Bioresour. Technol. 121, 362–368.
Lillenberg, M., Yurchenko, S., Kipper, K., Herodes, K., Pihl, V., Lohmus, R., Ivask, M., Kuu, A., Kutti, S., Litvin, S.V., Nei, L., 2010. Presence of fluoroquinolones and sulphonamides in urban sewage sludge and their degradation as a result of composting. Int. J. Environ. Sci. Technol. 7, 307–312.
Liu, J., Lu, Z., Yang, J., Xing, M., Yu, F., Guo, M., 2012. Effect of earthworms on the performance and microbial communities of excess sludge treatment process in vermifilter. Bioresour. Technol. 117, 214–221.
Lv, B., Xing, M., Yang, J., 2016. Speciation and transformation of heavy metals during vermicomposting of animal manure. Bioresour. Technol. 209, 397–401.
Lv, B., Zhang, D., Cui, Y., Yin, F., 2018. Effects of C/N ratio and earthworms on greenhouse gas emissions during vermicomposting of sewage sludge. Bioresour. Technol. 268, 408–414.
Macias-Corral, M.A., Cueto-Wong, J.A., Morán-Martínez, J., Reynoso-Cuevas, L., 2019. Effect of different initial C/N ratio of cow manure and straw on microbial quality of compost. Int. J. Recycl. Org. Waste Agric. 8, 357–365.
Mainoo, N.O.K., Barrington, S., Whalen, J.K., Sampedro, L., 2009. Pilot-scale vermicomposting of pineapple wastes with earthworms native to Accra, Ghana. Bioresour. Technol. 100, 5872–5875.
Malinska, K., Zabochnicka-Swiatek, M., Cáceres, R., Marfàb, O., 2016. The effect of precomposted sewage sludge mixture amended with biochar on the growth and reproduction of *Eisenia fetida* during laboratory vermicomposting. Ecol. Eng. 90, 35–41.
Manyuchi, M., Phiri, A., 2013. Vermicomposting in solid waste management: a review. Int. J. Sci. Eng. Technol. 2, 1234–1242.
Mateo-Sagasta, J., Raschid-Sally, L., Thebo, A., 2015. Global Wastewater and Sludge Production. Treatment and Use. In Wastewater - Economic Asset in an Urbanizing World. Springer, Dordrecht, pp. 15–38.
Mousavi, S.M., Brodie, G., Payghamzadeh, K., Raiesi, T., Srivastava, A.K., 2022. Lead (Pb) bioavailability in the environment, its exposure and effects. J. Environ. Health Res 10, 1.
Negi, R., Suthar, S., 2018. Degradation of paper mill wastewater sludge and cow dung by brown-rot fungi Oligoporus placenta and earthworm (*Eisenia fetida*) during vermicomposting. J. Clean. Prod. 201, 842–852.
Nigussie, A., Kuyper, T.W., Bruun, S., De Neergaard, A., 2016. Vermicomposting as a technology for reducing nitrogen losses and greenhouse gas emissions from small-scale composting. J. Clean. Prod. 139, 429–439.
Oudart, D., 2013. Modeling of the stabilization of organic matter and gaseous emissions during the composting of livestock effluents (Doctoral dissertation, INSA Toulouse).
Pathma, J., Sakthivel, N., 2012. Microbial diversity of vermicompost bacteria that exhibit useful agricultural traits and waste management potential. SpringerPlus 1, 1–19.
Pattnaik, S., Reddy, M.V., 2010. Nutrient status of vermicompost of urban green waste processed by three earthworm species *Eisenia fetida, Eudrilus eugeniae, and Perionyx excavatus*. Appl. Environ. Soil Sci. 2010, 13.
Pigatin, L.B.F., Atoloye, I.O., Obikoya, O.A., Borsato, A.V., Rezende, M.O.O., 2016. Chemical study of vermicomposted agroindustrial wastes. Int. J. Recycl. Org. Waste Agric. 5, 55–63.
Pramanik, P., Ghosh, G.K., Ghosal, P.K., Banik, P., 2007. Changes in organic C, N, P and K and enzyme activities in vermicompost of biodegradable organic wastes under liming and microbial inoculants. Bioresour. Technol. 98, 2485–2494.
Raj, D., Antil, R.S., 2011. Evaluation of maturity and stability parameters of composts prepared from agro-industrial wastes. Bioresour. Technol. 102, 2868–2873.
Ravindran, B., Contreras-Ramos, S.M., Sekaran, G., 2015. Changes in earthworm gut associated enzymes and microbial diversity on the treatment of fermented tannery waste using *epigeic* earthworm *Eudrilus eugeniae*. Ecol. Eng. 74, 394–401.
Rékási, M., Mazsu, N., Draskovits, E., Bernhardt, B., Szabó, A., Rivier, P.A., Farkas, C., Borsányi, B., Pirkó, B., Molnár, S., Kátay, G., 2019. Comparing the agrochemical properties of compost and vermicomposts produced from municipal sewage sludge digestate. Bioresour. Technol. 291, 121861.
Rini, J., Deepthi, M.P., Saminathan, K., Narendhirakannan, R.T., Karmegam, N., Kathireswari, P., 2020. Nutrient recovery and vermicompost production from livestock solid wastes with *epigeic* earthworms. Bioresour. Technol. 313, 123690.
Sánchez-Monedero, M.A., Serramiá, N., Civantos, C.G.-O., Fernández-Hernández, A., Roig, A., 2010. Greenhouse gas emissions during composting of two-phase olive mill wastes with different agroindustrial by-products. Chemosphere 81 (1), 18–25.
Sharma, K., Garg, V.K., 2018. Comparative analysis of vermicompost quality produced from rice straw and paper waste employing earthworm *Eisenia fetida* (Sav.). Bioresour. Technol. 250, 708–715.
Singh, D., Suthar, S., 2012. Vermicomposting of herbal pharmaceutical industry waste: earthworm growth, plant-available nutrient and microbial quality of end materials. Bioresour. Technol. 112, 179–185.
Singh, N., Tang, Y., Ogunseitan, O.A., 2020. Environmentally sustainable management of used personal protective equipment. Environ. Sci. Technol. 54 (14), 8500–8502.
Sinha, R.K., Herat, S., Agarwal, S., Asadi, R., Carretero, E., 2002. Vermiculture technology for environmental management: Study of action of earthworms *Eisinia foetida, Eudrilus euginae* and *Perionyx excavatus* on biodegradation of some community wastes in India and Australia. Environmentalist 22, 261–268.
Soobhany, N., 2019. Insight into the recovery of nutrients from organic solid waste through biochemical conversion processes for fertilizer production. A Rev. J. Clean. Prod. 241, 118413.
Soobhany, N., Mohee, R., Garg, V.K., 2015. Experimental process monitoring and potential of *Eudrilus eugeniae* in the vermicomposting of organic solid waste in Mauritius. Ecol. Eng. 84, 149–158.
Srivastava, V., Goel, G., Thakur, V.K., Singh, R.P., Ferreira de Araujo, A.S., Singh, P., 2020. Analysis and advanced characterization of municipal solid waste vermicompost maturity for a green environment. J. Environ. Manag. 255, 109914.
Sudkolai, S.T., Nourbakhsh, F., 2017. Urease activity as an index for assessing the maturity of cow manure and wheat residue vermicomposts. Waste Manag. 64, 63–66.
Suthar, S., 2010. Recycling of agro-industrial sludge through vermitechnology. Ecol. Eng. 36, 1028–1036.
Suthar, S., Gairola, S., 2014. Nutrient recovery from urban forest leaf litter waste solids using Eisenia fetida. Ecol. Eng. 71, 660–666.
Tognetti, C., Laos, F., Mayyarino, M.J., Hernańdez, M.T., 2005. Composting vs. vermicomposting: a comparison of end product quality. Compost Sci. Util. 13, 6–13.
Tognetti, C., Mazzarino, M.J., Laos, F., 2007. Co-composting biosolids and municipal organic waste: effects of process management on stabilization and quality. Biol. Fert. Soils 43, 387–397.
Tripetchkul, S., Pundee, K., Koonsrisuk, S., Akeprathumchai, S., 2012. Co-composting of coir pith and cow manure: initial C/N ratio vs physico-chemical changes. Int. J. Recycl. Org. Waste Agric. 1, 15.
Van Vliet, P.C., Beare, M.H., Coleman, D.C., Hendrix, P.F., 2004. Effects of enchytraeids (Annelida: Oligochaeta) on soil carbon and nitrogen dynamics in laboratory incubations. Appl. Soil Ecol. 25, 147–160.
Vochozka, M., Maroušková, A., Šuléř, P., 2017. Obsolete laws: economic and moral aspects, case study composting standards. Sci. Eng. Ethics 23 (6), 1667–1672.
Wang, J., Hu, Z., Xu, X., Jiang, X., Zheng, B., Liu, X., Pan, X., Kardol, P., 2014. Emissions of ammonia and greenhouse gases during combined pre-composting and vermicomposting of duck manure. Waste Manag. 34, 1546–1552.
Wang, Y., Tang, Y., Li, M., Yuan, Z., 2021. Aeration rate improves the compost quality of food waste and promotes the decomposition of toxic materials in leachate by changing the bacterial community. Bioresour. Technol. 340, 125716.
Wani, K.A., Rao, R.J., 2013. Bioconversion of garden waste, kitchen waste and cow dung into value-added products using earthworm *Eisenia fetida*. Saudi J. Biol. Sci. 20, 149–154.
Wu, H.P., Lai, C., Zeng, G.M., Liang, J., Chen, J., Xu, J.J., Dai, J., Li, X.D., Liu, J.F., Chen, M., Lu, L.H., Hu, L., Wan, J., 2017. The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review. Crit. Rev. Biotechnol. 2, 754–764.
Yadav, A., Garg, V.K., 2016. Vermiconversion of biogas plant slurry and parthenium weed mixture to manure. Int. J. Recycl. Org. Waste Agric. 5, 301–309.
Yadav, A., Garg, V.K., 2019. Biotransformation of bakery industry sludge into valuable product using vermicomposting. Bioresour. Technol. 274, 512–517.
Yadav, K.D., Tare, V., Ahammed, M.M., 2012. Integrated composting vermicomposting process for stabilization of human faecal slurry. Ecol. Eng. 47, 24–29.
Yang, F., Li, G., Zang, B., Zhang, Z., 2017. The maturity and $CH_4$, $N_2O$, $NH_3$ emissions from vermicomposting with agricultural waste. Compost Sci. Util. 25, 262–271.
Zhang, S., Chen, Z., Wen, Q., Yang, L., Wang, W., Zheng, J., 2016. Effectiveness of bulking agents for co-composting penicillin mycelial dreg (PMD) and sewage sludge in pilotscale system. Environ. Sci. Pollut. Res. Int. 23 (2), 1362–1370.
Zhi-wei, S., Tao, S., Wen-jing, D., Jing, W., 2019. Investigation of rice straw and kitchen waste degradation through vermicomposting. J. Environ. Manag. 243, 269–272.
Zziwa, A., Jjagwe, J., Kizito, S., Kabenge, I., Komakech, A.J., Kayondo, H., 2021. Nutrient recovery from pineapple waste through controlled batch and continuous vermicomposting systems. Environ. Manag. 279, 111784.