

## Article

# Carbon Dioxide and Methane Emissions during the Composting and Vermicomposting of Sewage Sludge under the Effect of Different Proportions of Straw Pellets

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**Abstract:** Owing to rapid population growth, sewage sludge poses a serious environmental threat across the world. Composting and vermicomposting are biological technologies commonly used to stabilize sewage sludge. The objective of this study was to assess the carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) emissions from sewage sludge composting and vermicomposting under the influence of different proportions of straw pellets. Four treatments were designed, by mixing the initial sewage sludge with varying ratio of pelletized wheat straw (0, 25%, 50%, and 75% (*w/w*)). The experiment was conducted for 60 days, and *Eisenia andrei* was used for vermicomposting. The results revealed that the mixing ratio influenced CO<sub>2</sub> ( $F = 36.1, p = 0.000$ ) and CH<sub>4</sub> ( $F = 73.9, p = 0.000$ ) emissions during composting and CO<sub>2</sub> ( $F = 13.8, p = 0.000$ ) and CH<sub>4</sub> ( $F = 4.5, p = 0.004$ ) vermicomposting. Vermicomposting significantly reduced CH<sub>4</sub> emissions by 18–38%, while increasing CO<sub>2</sub> emissions by 64–89%. The mixing agent (pelletized wheat straw) decreased CO<sub>2</sub> emission by 60–70% and CH<sub>4</sub> emission by 30–80% compared to control (0%). The mass balance indicated that 5.5–10.4% of carbon was loss during composting, while methane release accounted for 0.34–1.69%, and CO<sub>2</sub> release accounted for 2.3–8.65%. However, vermicomposting lost 8.98–13.7% of its carbon, with a methane release of 0.1–0.6% and CO<sub>2</sub> release of 5.0–11.6% of carbon. The carbon loss was 3.3–3.5% more under vermicomposting than composting. This study demonstrated that depending on the target gas to be reduced, composting and vermicomposting, as well as a mixing agent (pelletized wheat straw), could be an option for reducing greenhouse gas emissions (i.e. CH<sub>4</sub>, CO<sub>2</sub>).



**Citation:** Dume, B.; Hanc, A.; Svehla, P.; Míchal, P.; Chane, A.D.; Nigussie, A. Carbon Dioxide and Methane Emissions during the Composting and Vermicomposting of Sewage Sludge under the Effect of Different Proportions of Straw Pellets. *Atmosphere* **2021**, *12*, 1380. <https://doi.org/10.3390/atmos12111380>

Academic Editor: Anthony R. Lupo

Received: 16 September 2021

Accepted: 19 October 2021

Published: 22 October 2021

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**Keywords:** thermophilic; earthworms; biosolids; sewage sludge; composting

## 1. Introduction

The world generates approximately 1.3 billion metric tons of solid waste, which is nearly double the amount generated a decade ago [1]. Solid waste generation is expected to be more than double by 2025 [2]. The annual increase in solid waste generation is inextricably linked to the global population's rapid growth and urbanization rate. Municipal solid waste (MSW) has primarily been disposed of in urban areas around the world through landfilling, incineration, and centralized composting and anaerobic digestion facilities. These processes result in direct and indirect emissions of greenhouse gases (GHGs) such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and non-methane hydrocarbons (NMHCs), accounting for approximately 3–4% of anthropogenic GHG emissions in terms of the CO<sub>2</sub>-equivalent (CO<sub>2</sub>-e) [3]. The anaerobic decomposition of these wastes in landfills produces CH<sub>4</sub> emissions, which contribute significantly to the global greenhouse budget [4].

Sewage sludge is a residual, semi-solid material produced as a by-product of biological wastewater treatment or municipal wastewater treatment [5,6]. Due to the putrescible

characteristics of sewage sludge, a large amount produced in recent decades represents a rising trend, and improper disposal or management has resulted in serious environmental pollution, posing a waste management challenge [5,7].

Inadequate sewage sludge management causes secondary pollution such as pathogenic microbes, organic micropollutants, and toxic heavy metals; thus, sustainable and eco-friendly sewage sludge management is urgently needed [8].

According to He et al. [9], the European Union currently produces more than 10.96 million tons of sewage sludge per year and China produces 40 million tons of sewage sludge with an 80% moisture content [10], both of which are increasing due to both accelerated urbanization and the increased capacity of municipal wastewater treatment facilities [11,12]. In the past, sewage sludge was disposed of through incineration, landfilling, or ocean disposal [13].

Composting and vermicomposting are effective and low-cost methods for managing and reusing sewage sludge because the products are safe and stable, and can be used as organic fertilizer or soil conditioner for farming [14–16]. However, harmful gases such as ammonia ( $\text{NH}_3$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and methane ( $\text{CH}_4$ ) emitted because of poor composting process management reduce not only the agronomic value of compost as a soil fertilizer or amendment but also the environmental benefits of composting [17,18]. Researchers have become interested in  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emissions during the composting process as global warming worsens and the greenhouse effect intensifies [19,20].

Two of the most significant greenhouse gases in the atmosphere are methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ). On a mass basis, methane is more radiatively powerful than  $\text{CO}_2$  and the current global warming potential of  $\text{CH}_4$  is 34 times greater than that of  $\text{CO}_2$  over a 100-year period [21].

Concerning the aforementioned issues, substantial research on sewage sludge composting has been conducted in recent decades, with a particular emphasis on the use of various additives to reduce greenhouse gas emissions [22,23]. Although earthworms do not produce these gases, they can have a significant impact on the physicochemical properties of the feeding substrate, thereby indirectly affecting gas-producing processes and thus  $\text{CO}_2$  and  $\text{CH}_4$  emissions.

The effects of earthworms on greenhouse gas emissions are complicated and no agreement has been reached. Earthworms, for example, increased  $\text{N}_2\text{O}$  and  $\text{CO}_2$  emissions from soils by 42% and 33%, respectively [24]. Others found that earthworms increased  $\text{CO}_2$  emissions but had no effect on  $\text{N}_2\text{O}$  fluxes from soils [25,26]. Similarly, the study in [27] demonstrated that vermicomposting of household waste produced more  $\text{CO}_2$  and  $\text{CH}_4$ , but produced less  $\text{N}_2\text{O}$  than traditional composting.

The majority of previous composting and vermicomposting studies focused on the feasibility of different organic wastes, the factors influencing earthworm growth and reproduction rates, and the quality of composts and vermicompost [28,29]. Furthermore, several recent studies [24,30] have focused on the effects of earthworms on GHG emissions from soils. However, there are limited studies on carbon dioxide and methane emissions during composting and vermicomposting of organic wastes, specifically sewage sludge, with varying ratio of additive materials. As a result, the goal of this study was to assess the carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) emissions from sewage sludge composting and vermicomposting under the influence of different proportions of straw pellets.

## 2. Materials and Methods

### 2.1. Raw Materials

The study made use of unstabilized sewage sludge and straw pellets mixed with water. The freshly deposited sewage sludge (SS) used in the experiments originated from a wastewater treatment plant in the Czech Republic, where thousands of people live, and had a dry matter content of 13.3%. A dried pelletized wheat straw (PWS) with a diameter of 10 mm was provided by the Granofyt Ltd. Company (Chrást'any, Czechia). Dry straw pellets were mixed with hot water at a rate of 4 L per 1 kg of straw pellets. After

mixing, the wet pellets were added to the sludge. The resulting material was put into aerobic fermenters for composting and the same mixing materials (treatments) were also transferred to worm bins for vermicomposting. The experiment was carried out at the Research Station of the Czech University of Agriculture in Červený Újezd, with samples subsequently analyzed at the Life Science laboratories of the Czech University in Prague. The selected chemical properties of the sewage sludge and pelletized wheat straw are listed in Table 1, while the treatments on the initial day (day 0) are listed in Table 2.

**Table 1.** Selected chemical properties of the sewage sludge and pelletized wheat straw.

Parameters	Sewage Sludge (SS)	Pelletized Wheat Straw (PWS)
pH	6.99 ± 0.017	8.30 ± 0.300
EC (mS/cm)	0.617 ± 0.064	0.680 ± 0.040
TC (%)	32.95 ± 0.150	42.6 ± 0.207
TN (%)	5.36 ± 0.017	0.8 ± 0.069
C:N	6.15 ± 0.011	53.2 ± 4.388

Values indicate mean ± standard error ( $n = 3$ ).

**Table 2.** Selected chemical properties of the treatments on the initial day (day 0).

Treatments	pH	EC(mS/cm)	TC (%)	TN (%)	C:N
T1	6.99 ± 0.017	0.617 ± 0.064	32.9 ± 0.150	5.36 ± 0.017	6.15 ± 0.023
T2	7.32 ± 0.064	0.633 ± 0.046	35.36 ± 0.133	1.98 ± 0.121	18.03 ± 1.11
T3	7.64 ± 0.144	0.649 ± 0.035	37.77 ± 0.139	1.34 ± 0.040	28.17 ± 0.826
T4	7.97 ± 0.219	0.664 ± 0.029	40.18 ± 0.167	1.05 ± 0.029	38.36 ± 1.172

T1= 100% SS; T2= 75% SS + 25 % PWS; T3= 50 % SS + 50 % PWS; and T4 =25 % SS + 75 % PWS ( $w/w$ ). Values indicate mean ± standard error ( $n = 3$ ).

## 2.2. Experimental Setup

### Composting and Vermicomposting

The experiment consisted of four treatments obtained by mixing the sewage sludge (SS) with pelletized wheat straw (PWS) at different mixing ratio including, T1 (100% SS (control)), T2 (75% SS + 25% PWS), T3 (50% SS + 50% PWS), and T4 (25% SS + 75% PWS;  $w/w$ ). To avoid earthworm mortality and to allow earthworms to return to suitable conditions, the substrate (3 L of apple pomace) containing earthworms was placed into the tray from the side. After mixing the materials (SS and PWS) at different percentage proportions, the treatments were transferred to worm-bins for vermicomposting in a specially adopted laboratory with controlled conditions (temperature 22 °C, relative humidity 80%) for 60 days. Each worm-bin received 377 (57.4 g) pieces of adult *Eisenia andrei* earthworms per treatment, with the initial average weight and number of earthworms at 19.13 g/kg and 126 pieces/kg, respectively, of the substrate. The moisture level of the material was maintained at about 70–80% of the wet mass throughout the vermicomposting stage by spraying the surface with water at two-day intervals and the same treatments used for vermicomposting were also transferred to the fermenter barrels for 60 days of composting. Three replications were conducted for all the treatments.

### 2.3. Carbon Dioxide (CO<sub>2</sub>) and Methane (CH<sub>4</sub>) Measurements during Composting and Vermicomposting

The CO<sub>2</sub> and CH<sub>4</sub> concentrations were measured using a closed chamber technique during composting and vermicomposting. A tight-fitting lid with two ports for headspace gas-sampling and air temperature measurement was used to connect one side of a plastic tube to closed barrels for composting and to a worm bin for vermicomposting, while the other side of the plastic tube was connected to instruments during the data collection. For 60 days, measurements were taken twice per day at 12 h intervals using the Gasko Infrared

Gas Analyzer [31]. To calculate the cumulative CO<sub>2</sub> and CH<sub>4</sub> emissions, we added daily values to obtain the total cumulative gas emissions over the course of the experiment [31].

$$A_{t(ab)} = \frac{(t_b - t_a) \cdot (F_{ta} + F_{tb})}{2} \quad (1)$$

where  $A_{t(ab)}$  is the cumulative emission between the measurement days (between  $t_a$  and  $t_b$ ),  $t_a$  and  $t_b$  are the measurement dates, and  $F_{ta}$  and  $F_{tb}$  are the gas fluxes on the two measurement dates. Therefore, the total cumulative emissions were calculated as the sum of cumulative emissions on each day using Equation (2):

$$\text{Total cumulative emission} = \sum A_{t(ab)} \quad (2)$$

C losses during composting and vermicomposting were calculated as:

$$C \text{ loss}(\%) = \frac{(C_{\text{initial}} - C_{\text{ending}})}{C_{\text{initial}}} \quad (3)$$

#### 2.4. Analysis of Total Carbon (TC), Total Nitrogen (TN), pH, and EC

The representative composite samples (about 150 g of wet basis per treatment) were taken, freeze-dried (−25 °C), lyophilized, and ground for the total carbon (TC) and total nitrogen (TN) analysis, whereas a 30 g sample was frozen at 4 °C for the pH and EC determination. Standard methods were used to determine TC, TN, pH, and EC from the samples. The pH and electrical conductivity (EC) were measured in distilled water at a 1:5 ( $w/v$ ) ratio. The pH-H<sub>2</sub>O and the electrical conductivity (EC) were tested using a WTW pH 340i and WTW cond 730 (1:5  $w/v$  dry basis) according to [32]. Inductively coupled plasma optical emission spectrometry (ICP-OES, VARIAN VistaPro, Varian, Australia) with axial plasma configuration was used to determine TC and TN in accordance with [33].

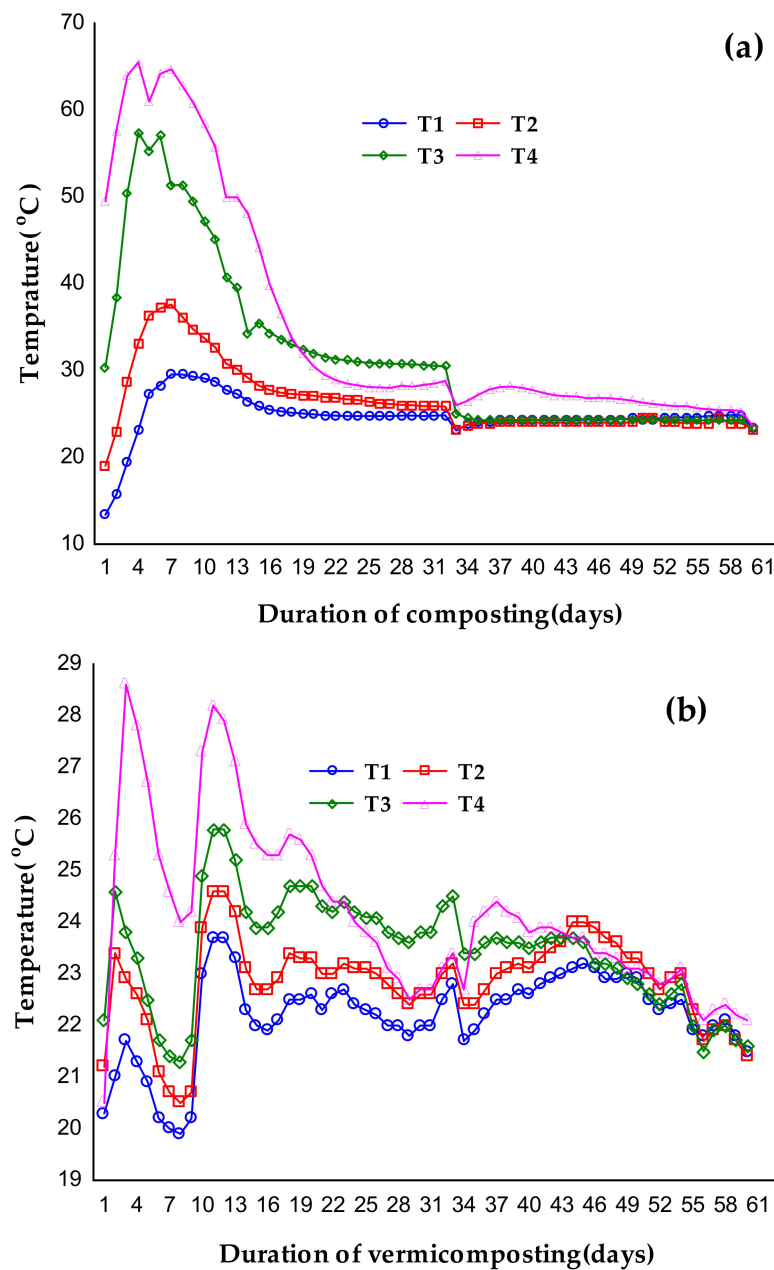
#### 2.5. Statistical Analyses

The statistical analyses were carried out using the R version 4.0.2 statistical package. ANOVA was used to test whether there was a significant difference between the composting method and mixing ratio in GHGs (i.e. CO<sub>2</sub> and CH<sub>4</sub>) emissions and properties of final product. Tukey HSD test was used to compare the treatment means if the effect of the factors was significant at  $p < 0.05$ .

### 3. Results and Discussions

#### 3.1. Temperature during Composting and Vermicomposting

During the composting process, the temperature in each treatment reached its maximum, with significant ( $F = 18.6$ ,  $p = 0.000$ ) differences among the treatments (Figure 1a). On days 3 and 2, the temperatures of two treatments (T3 and T4) rapidly reached the thermophilic stage (>50 °C). T4 reached a maximum thermophilic phase of 65.5 °C in four days, while T3 reached 57.4 °C in four days. The thermophilic phase of T4 lasted 14 days, while that of T3 lasted 10 days. The maximum temperature for the remaining treatments was 37.6 °C for T2 and 29.55 °C for T1, with temperatures gradually decreasing until the experiment ended. Thus, the addition of pelletized wheat straw resulted in a more intensive decomposition in the thermophilic phase, but the degradation process resulted in less heat in these mixtures during the cooling phase due to the depletion of easily degradable organic compounds [34]. T1 (control) and T2 (25% PWS) delayed reaching the thermophilic stage and had no thermophilic phase at all; the maximum temperature for T2 was 37.6 °C and 29.55 °C for the control, and they matured within the mesophilic temperatures. This may have been because of the high moisture content of these treatments.



**Figure 1.** Evolution of temperatures during the composting (a) and vermicomposting (b) processes.

In the laboratory, the vermicomposters were kept at 22 °C. The temperatures recorded during the vermicomposting are shown in Figure 1b. The temperature of the vermicomposting was in the 19 °C to 28 °C range, which was obviously less than the thermophilic compost range and was favorable for earthworms [35]. Statistical analysis revealed that there were significant temperature differences among the treatments during the vermicomposting period ( $F = 31, p = 0.000$ ). At the start of the process, the temperature of the vermicomposting material rose to 28.6 °C only for T4.

### 3.2. pH and EC

The pH of the final compost and vermicompost for each treatment is shown in Table 3. The proportions of pelletized wheat straw in the mixtures resulted in lesser pH values during vermicomposting [36]. This was probably due to the high content of organic acids (e.g., succinic and maleic acid) and was directly proportional to the amount of straw in the treatments [36]. Other researchers [36–39] reported similar pH behaviors during

the vermicomposting of sewage sludge, crop straw, municipal solid waste, and livestock manure. Gigliotti et al. [40] reported that the mineralization of organic matter generally leads to the release of ammonium and volatile ammonia, which increases pH levels. The release of low-molecular weight organic acids from organic decomposition, as well as the increase in nitrification may reduce the pH during vermicomposting [37]. The pH of the vermicompost might indicate that a more intense decomposition reaction occurs during vermicomposting than composting.

**Table 3.** Selected chemical properties of the end-product compost and vermicompost.

Composting Method	Treatments	pH	EC (mS/cm)	TC (%)	TN (%)	C:N
Composting	T1	8.4 ± 0.069	1.90 ± 0.098	29.52 ± 0.421	4.55 ± 0.081	6.50 ± 0.012
	T2	8.3 ± 0.052	1.43 ± 0.052	32.43 ± 0.456	3.69 ± 0.017	8.84 ± 0.185
	T3	8.4 ± 0.046	1.94 ± 0.081	34.45 ± 0.883	3.27 ± 0.029	10.57 ± 0.375
	T4	8.0 ± 0.035	0.80 ± 0.035	37.95 ± 0.012	2.76 ± 0.087	13.88 ± 0.462
Vermicomposting	T1	6.7 ± 0.670	0.644 ± 0.023	28.43 ± 0.185	4.22 ± 0.127	6.77 ± 0.150
	T2	6.5 ± 0.866	1.186 ± 0.127	31.96 ± 0.514	3.58 ± 0.023	8.94 ± 0.202
	T3	6.5 ± 0.081	0.802 ± 0.225	34.38 ± 0.652	2.95 ± 0.087	11.72 ± 0.537
	T4	6.6 ± 0.179	1.21 ± 0.069	35.32 ± 0.214	3.08 ± 0.035	12.15 ± 0.185

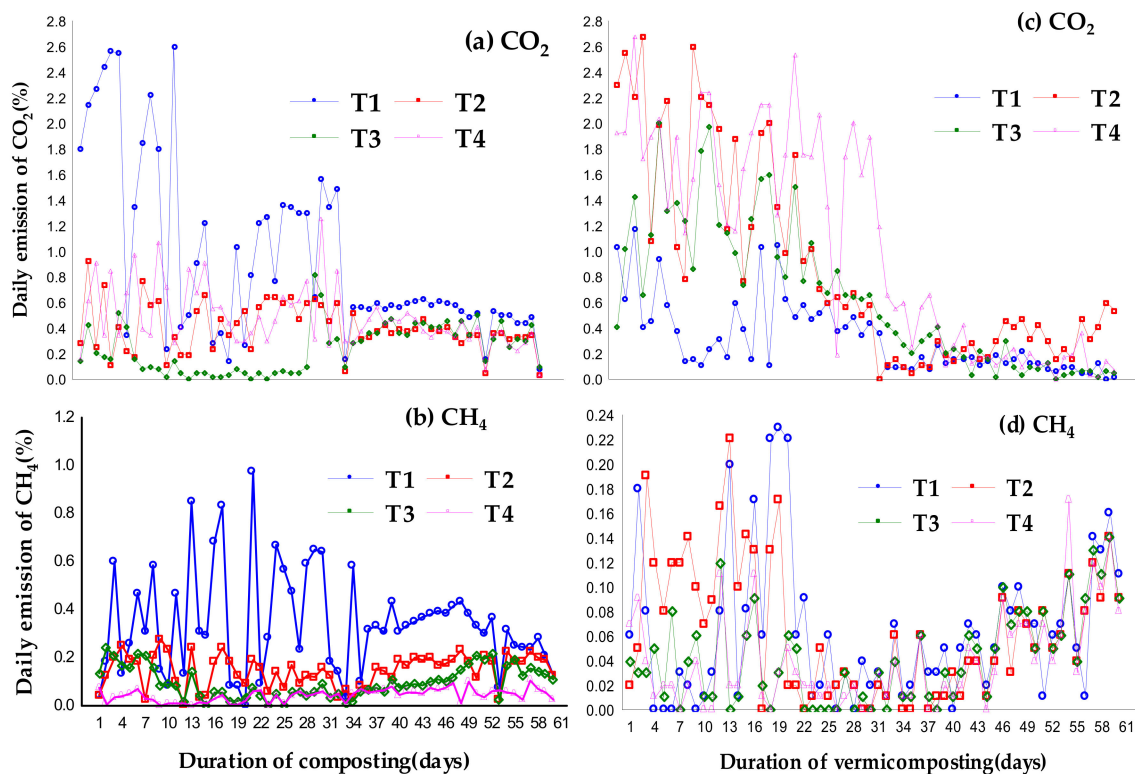
T1= 100% SS; T2= 75% SS + 25 % PWS; T3= 50 % SS + 50% PWS; and T4 =25 % SS + 75 % PWS (*w/w*). The values indicate mean ± standard error (n = 3).

The EC value of compost was greater than that of the vermicompost made from the same raw materials and treatments (Table 3). The EC increased in all treatments, which could be explained by the release of bonded elements during earthworm digestion [41,42], as well as by the mineral release during organic matter decomposition in the form of cations in the vermicompost [43]. The final EC for all treatments was less than 2 dS/m [44], indicating that the vermicompost/compost was suitable for plant application. The increased EC during the vermicomposting processes is consistent with that of previous researchers [45,46] and is most likely due to organic matter degradation, which releases minerals such as exchangeable Ca, Mg, K, and P in the available forms, that is, in the form of cations in the vermicompost and compost [43].

### 3.3. Carbon Dioxide(CO<sub>2</sub>) and Methane(CH<sub>4</sub>) Emissions during Composting and Vermicomposting

#### 3.3.1. Carbon Dioxide (CO<sub>2</sub>)

The CO<sub>2</sub> emissions increased at the start of the composting (Figure 2a) and vermicomposting (Figure 2c) due to the rapid decomposition of easily degradable organic matter, and then gradually decreased until the end of the composting/vermicomposting. This finding confirms those reported by Awasthi et al. [47] and Meng et al. [15] during sewage sludge composting. During the first 13 days of composting, CO<sub>2</sub> emissions in the control (T1) were greater than in the other treatments (T2, T3, and T4). However, CO<sub>2</sub> emissions were less in the T1 (control) during vermicomposting. As the earthworms inhibited microbial activity and reduced the readily available OM, this result was possible [48]. There were significant differences in CO<sub>2</sub> (F = 36.1, *p* = 0.000) emissions among the treatments during the composting and vermicomposting CO<sub>2</sub> (F = 13.8, *p* = 0.000). These findings imply that pelletized wheat straw may be lost in the inhibition after the thermophilic stage, most likely as a result of high-temperature self-degradation [49]. This conclusion is supported by the temperature and pH of T1, T2, T3, and T4. In all treatments, there was a significant decrease in CO<sub>2</sub> emissions on day 14 and a minor peak on day 20 (Figure 2a). This finding could be attributed to the anaerobic environment created by the rapid decomposition of OM during the first 14 days. The anaerobic conditions were destroyed by the subsequent turn on day 10. Previous studies [47] on sewage sludge composting reported similar results, in which CO<sub>2</sub> emissions were higher at the start of the composting period, with the highest levels observed on day 2, and then gradually decreased until the end of the thermophilic phase.



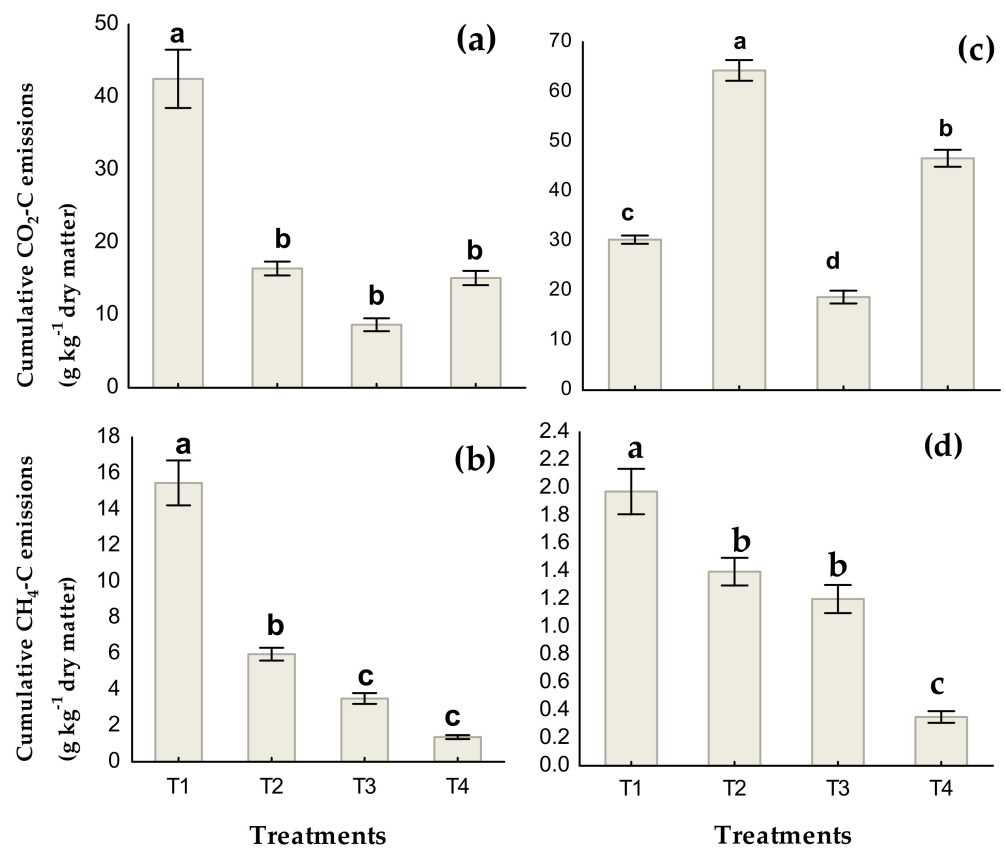
**Figure 2.** Daily emissions of CO<sub>2</sub> and CH<sub>4</sub> during composting (a,b) and vermicomposting (c,d).

### 3.3.2. Methane (CH<sub>4</sub>)

The amount of CH<sub>4</sub> produced by all the treatments used during the composting (Figure 2b) and vermicomposting (Figure 2d) processes are shown in Figure 2. There were significant differences in the CH<sub>4</sub> ( $F = 73.9, p = 0.000$ ) emitted during composting and the CH<sub>4</sub> ( $F = 4.5, p = 0.004$ ) emitted from all the treatments during vermicomposting. The CH<sub>4</sub> concentrations in all the treatments peaked relatively early (within 1–3 weeks) in both the composting and vermicomposting processes, and then gradually declined until the experiment ended. As a result, it is reasonable to assume that the CH<sub>4</sub> emissions occur at the beginning of the process. Several studies have discovered that the greatest levels of CH<sub>4</sub> emissions occur at the beginning of the composting and vermicomposting processes [50]. CH<sub>4</sub>, a major GHG produced during composting and vermicomposting, significantly contributes to global warming. CH<sub>4</sub> production is attributed to the methanogen deoxidization of CO<sub>2</sub>/H<sub>2</sub> and acetic acid in the presence of low oxygen [51]. Following that, as the organic matter (OM) decomposed and oxygen was replenished through turning, the CH<sub>4</sub> emissions of all the treatments fell sharply and remained lowered throughout the composting and vermicomposting maturation phases.

The observed pattern of CH<sub>4</sub> emissions in this study is similar to the patterns reported by Ma et al. [52] and Wang et al. [53]. As microorganisms can rapidly degrade organics in the thermophilic phase, there is a dramatic reduction in O<sub>2</sub> levels in the compost [54]. Composting emitted more CH<sub>4</sub> than vermicomposting in all the treatments and the greater results were measured in the control area.

Total cumulative CO<sub>2</sub> levels differed significantly ( $p < 0.001$ ) by the composting method (Figure 3). Vermicomposting increased total cumulative CO<sub>2</sub> emissions in comparison to thermophilic composting. Composting reduced total cumulative CH<sub>4</sub> emissions ( $p < 0.001$ ). When compared to thermophilic composting, vermicomposting reduced CH<sub>4</sub> emissions by 74.5% from a high proportion of pelletized wheat straw T4 treatments.



**Figure 3.** Total cumulative emissions of CO<sub>2</sub>-C (a) and CH<sub>4</sub>-C (b) after 60 days of composting, and CO<sub>2</sub>-C (c) and CH<sub>4</sub>-C (d) during vermicomposting. The bars indicate the standard error of the mean (n = 3). Different letters indicate significant differences among the treatments ( $p < 0.05$ ).

### 3.4. Total Carbon(TC), Total Nitrogen(TN), and the C:N Ratio

The content of TC, TN, and C:N ratio for all the treatments is shown in Table 3. When compared to the initial treatments, the TC and C:N contents of both compost and vermicompost decreased. However, the TN content of both compost and vermicompost increased. The loss of ammonia volatilization at relatively high temperatures, combined with a pH unsuitable for nitrification and denitrification, resulted in an increase in TN content [55]. According to Zhang et al. [56], the increase in TN during sludge vermicomposting was due to worm activity. Composting and vermicomposting both reduced the C:N ratio for all the treatments. Considering that it reflects stabilization and mineralization rates during vermicomposting, the C:N ratio indicates the maturity of compost/vermicompost [57]. The C:N ratio is an important metric for determining whether the compost/vermicompost product has been thoroughly stabilized. Microorganisms decompose biodegradable components and convert them to CO<sub>2</sub>, H<sub>2</sub>O, and to other small molecules during the composting/vermicomposting process. However, the rate of loss for organic N is less than that for organic C, resulting in a decrease in the C:N ratio during the composting/vermicomposting process. In general, the C:N ratio of fully decomposed compost/vermicompost should be between 15 and 20 [58]. The C:N ratio of all mixtures in this study followed the same trend, with statistically significant differences between the two composting processes (Table 3). Previous research [59] found that vermicomposting cow dung with vegetable waste reduced the C:N ratio by up to 50.86% and 48.88%. The final C:N ratio recorded for all the treatments was less than 20, which is within the recommended value for soil applications [60].



### 3.5. Carbon Balances

The mass balance analysis revealed that composting lost 5.54–10.42% of the total carbon across all treatments; total methane release accounted for 0.34–1.69%; and CO<sub>2</sub> release accounted for 2.3–8.65%. However, vermicomposting lost 8.98–13.73% of the total carbon, with a total methane release of 0.1–0.6% and CO<sub>2</sub> release of 5.03–11.61% of the initial total carbon (Table 4). These findings agree with those of Nigussie et al. [61] who demonstrated that organic carbon is lost during composting/vermicomposting. Thus, when compared to thermophilic composting, vermicomposting increased the total C loss by 3.3–3.5% (Table 4).

**Table 4.** Carbon loss (CH<sub>4</sub>-C and CO<sub>2</sub>-C) during composting and vermicomposting.

Total C Emission during Composting								
Trts	Initial C (g kg <sup>-1</sup> )	Ending C (g kg <sup>-1</sup> )	CH <sub>4</sub> -C (g kg <sup>-1</sup> )	CO <sub>2</sub> -C (g kg <sup>-1</sup> )	C Loss (%)	CH <sub>4</sub> -C Loss (%)	CO <sub>2</sub> -C Loss (%)	Unaccounted C (%)
T1	329.53	295.2	5.48	28.51	10.42	1.66	8.65	0.11
T2	353.62	324.38	5.97	16.42	8.29	1.69	4.64	1.96
T3	377.70	344	3.51	8.68	8.92	0.93	2.30	5.69
T4	401.78	379.5	1.37	15.11	5.54	0.34	3.76	1.44
Total C Emission during Vermicomposting								
Trts	Initial C (g kg <sup>-1</sup> )	Ending C (g kg <sup>-1</sup> )	CH <sub>4</sub> -C (g kg <sup>-1</sup> )	CO <sub>2</sub> -C (g kg <sup>-1</sup> )	C Loss (%)	CH <sub>4</sub> -C Loss (%)	CO <sub>2</sub> -C Loss (%)	Unaccounted C (%)
T1	329.53	284.3	1.97	30.28	13.73	0.60	9.19	3.94
T2	353.62	305.6	0.35	44.31	13.58	0.1	12.53	0.95
T3	377.70	343.8	1.20	18.73	8.98	0.32	5.03	3.63
T4	401.78	353.2	1.40	46.64	12.09	0.35	11.61	0.13

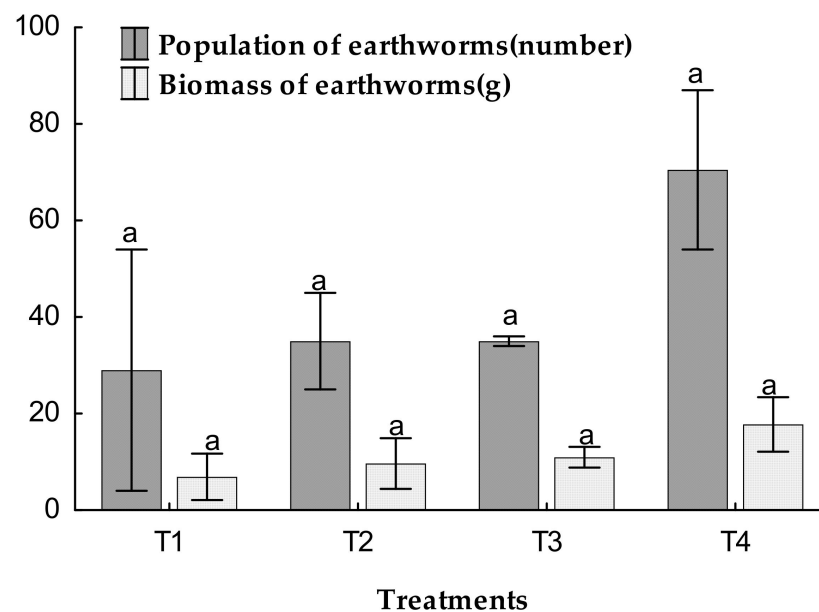
T1= 100% SS; T2= 75% SS + 25 % PWS); T3= 50% SS + 50 % PWS; and T4 =25 % SS + 75 % PWS (w/w).

Earthworms decomposing organic matter [24]; earthworms mixing the substrate and increasing the accessibility of the materials for decomposers (e.g. Fungi, bacteria); and earthworm casts increasing the decomposition [62] all contributed to greater C loss after vermicomposting. Unaccounted C ranged from 0.11 to 5.69% during composting and 0.13 to 3.94% during vermicomposting, which is consistent with previous research [63,64]. Unaccounted C indicates that C was not measured between sampling dates [63] and C losses due to volatile compounds [64].

### 3.6. Population and Biomass of Earthworms

The population (number) and biomass of earthworms (g) in all the treatments are shown in Figure 4.

The substrate ratio (pelletized wheat straw) had no effect on the relative change of the earthworm biomass ( $p = 0.49$ ) and population ( $p = 0.36$ ). The earthworm biomass increased in mixtures containing a high percentage of pelletized wheat straw (T4). Increased earthworm abundance reduced CH<sub>4</sub> emissions and accelerated the decomposition process. Vermicomposting increased CO<sub>2</sub> emissions, implying that vermicompost is further along in its decomposition process than thermophilic compost. These findings are consistent with those of Nigussie et al. [61] who found that vermicomposting reduced CH<sub>4</sub> while increasing CO<sub>2</sub> emissions.



**Figure 4.** Population (number) and biomass of earthworms (g) after 60 days of vermicomposting. Bars indicate the standard error of the mean ( $n = 3$ ).

#### 4. Conclusions

The composting and vermicomposting of sewage sludge produced significant amounts of  $\text{CO}_2$  ( $F = 36.1$ ,  $p = 0.000$ ) and  $\text{CH}_4$  ( $F = 73.9$ ,  $p = 0.000$ ), which were emitted during composting, and  $\text{CO}_2$  ( $F = 13.8$ ,  $p = 0.000$ ) and  $\text{CH}_4$  ( $F = 4.5$ ,  $p = 0.004$ ), which were emitted from all the treatments during vermicomposting. The greatest values were obtained at the start of the experiment and gradually decreased. The fate of C in the waste substrate is linked to the emission of  $\text{CH}_4$  and  $\text{CO}_2$  during composting and vermicomposting. Vermicomposting reduced  $\text{CH}_4$  emissions while also accelerating the decomposition process.  $\text{CO}_2$  and  $\text{CH}_4$  emissions were increased during composting at various proportions of added pelletized wheat straw. Vermicomposting increased  $\text{CO}_2$  emissions, implying that vermicompost is further along in its decomposition process. Vermicomposting significantly reduced  $\text{CH}_4$  emissions by 18–38%, while increasing  $\text{CO}_2$  emissions by 64–89%. The mixing agent (pelletized wheat) decreased  $\text{CO}_2$  emission by 60–70% and  $\text{CH}_4$  emission by 30–80% compared to control (0%). Increased earthworm abundance reduced  $\text{CH}_4$  emissions and increased  $\text{CO}_2$  emissions. The mass balance analysis indicated that 5.5–10.4% of carbon was lost by composting, methane release accounted for 0.34–1.69%, and  $\text{CO}_2$  release accounted for 2.3–8.65%. However, 8.98–13.7% of carbon was lost by vermicomposting with a methane release of 0.1–0.6% and  $\text{CO}_2$  release of 5.0–11.6% of C. Thus, when compared to thermophilic composting, vermicomposting increased the total C loss by 3.3–3.5%. This study demonstrated that depending on the target gas to be reduced, composting and vermicomposting, as well as a mixing agent (pelletized wheat straw), could be an option for reducing greenhouse gas emissions (i.e.  $\text{CH}_4$ ,  $\text{CO}_2$ ).

**Author Contributions:** Conceptualization, B.D., A.H. and P.S.; methodology, B.D., A.H. and P.S.; formal analysis, B.D., A.H. and P.S.; investigation, B.D.; resources, B.D., A.H. and P.S.; data curation, B.D., A.H. and P.S.; writing—original draft preparation, B.D., A.H. and P.S.; writing—review and editing, A.N.; visualization, B.D.; supervision, A.H. and P.S.; project administration, A.H.; funding acquisition, A.H.; sample and data collection, P.M. and A.D.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Ministry of Agriculture of the Czech Republic, grant number QK1910095.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The corresponding author can provide the data used in this study upon request.

**Acknowledgments:** 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 Christina Baker Starrman (<https://cbsciedit.com/>, accessed on 1 October 2021) for the revision of the English text.

**Conflicts of Interest:** The authors declare no conflict of interest.

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