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Nutrients Recovery during Vermicomposting of Cow Dung, Pig Manure, and Biochar for Agricultural Sustainability with Gases Emissions

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Abstract: An experimental vermicomposting system was established in purple soil present in Sichuan Basin, China. The purpose of vermicomposting (VC) was to recycle and manage organic waste materials; for instance, animal manure and crop residues are present in great quantity. A particular use of earthworms for VC is a valuable method for retrieving essential plant nutrients. Experimental vermicomposting followed by monitoring was conducted for two months in summer with an interval of fifteen days. Four treatments, COM (compost without earthworms), VCM (using cow manure), VPM (through pig manure), and VBC (using biochar), were applied with agricultural wastes such as rapeseed and wheat straw in combination with cow dung, pig manure, and biochar, respectively. One-way analysis of variance (ANOVA) was used to statistically analyze and interpret the nutrient change among different treatments. Post hoc analysis was done using Tukey's test. The experimental vermicomposting results revealed that VCM gives increased plant nutrients with a minimum C: N ratio (from 22.13 to 14.38) and a maximum increase in nitrogen concentrations (1.77 to 29.15 g kg^{-1}). A significant decrease in ammonia volatilization was observed in the order VCM > VBC > VPM when compared to COM. It was experimentally established that vermicomposting is the most suitable method for converting organic waste into nutrient-rich fertilizer with the least environmental pollution load.

Keywords: vermicompost; earthworms; agricultural wastes; nutrients; gases emissions; purple soil

1. Introduction

The excess use of nitrogen (N) fertilizers in agriculture is increasing rapidly for food and bioenergy production due to the world's fast-growing population. To protect the environment, many wastes such as agricultural manure and crop residues can be recycled in a better way than they are currently managed. According to an estimate, 2.6 million tons per day of municipal solid waste is produced globally, and the amount may reach up to 4.5 million tons per day by 2050, International Solid Waste Association (ISWA) [1]. Composting is a useful method to reuse wastes such as manure [2], while the vermicomposting technique is more beneficial compared to composting as it provides for improved bioavailability of all macro- and micronutrients [3]. Vermicompost is an organic fertilizer made up of waste material processed in the guts of earthworms, which contain microbes and enzymes that ingest and absorb the organic waste [4]. Vermicompost is an organic amendment rich in nutrients and active in the microbiological perspective as a result of the microbiological breakdown of organic matter [5]. Though some of the inorganic plant nutrients are already present in the soil, they are supplemented by gradual release during organic matter mineralization, thus creating a slow but constant source of nutrients. Vermicompost has been regarded as an ecofriendly alternative for the recycling of organic solid waste. It also acts as a soil conditioner that helps plant growth [6]. Aerobic composting has gained attention for remarkable recycling of organic solid waste [7], with high organic content and low cost [8], great nutritional capacity [9] of municipal solid waste, profitable application of the end product [10], and less ecological damage than incineration and landfilling if appropriately handled. *Eisenia fetida* is one of the most important family members of Lumbricidae that can frequently be used for vermicomposting [11]. Zhu and Zhu [12] also studied a dominant group of Lumbricidae from the soil fauna in purple soil, which was considered the most useful species for vermicomposting.

Biochar can also be utilized as a soil nutrient enrichment for improved production of crops and as a stimulator of composting substances that can further be used in horticulture and environmental purposes, for example, as a combination with manure for nutrient recycling [13]. Furthermore, sufficient information is not available for vermicompost production using biochar as an alternative to manure. Extensive diversity of organic litter consisting of animal dung, leftovers from industries, sewage muck, and agricultural residues were widely recycled to prepare vermicast using earthworm species [14,15].

Manure could play an important role in the cycling process to recover nutrients and part of energy sources [16]. Therefore, improper management may also cause environmental pollution. The crop residues from the fields are not rich in nitrogen and require supplementary material to fulfill soil microorganisms' nutrient requirements; hence, organic substrates are also provided to the soil during vermicomposting [17].

Among crops, rapeseed is considered rich in protein. Its leftovers after processing can be used as a vermicompost substrate [18]. Rapeseed is the largest cultivated crop in China and constitutes 20% of the world's production [19]. Wheat straw and rapeseed are important field crops cultivated in the winter season, producing large amounts of agricultural waste in upland areas of the Sichuan Basin. The interaction of earthworms with wheat straw and rapeseed has been studied during vermicomposting through different manure [20,21]. However, there is still a knowledge gap for the field-scale study to recover nutrients and emission of gases (NH_3 volatilization and GHGs) during nutrient recovery from agricultural organic waste.

Ammonia emissions produce adverse effects in the atmosphere by spreading atmospheric particulates and eutrophication and reducing nitrogen (N) efficiency [22]. Physical parameters additionally might also affect pH, temperature, and moisture [23]. NH_3 volatilization can be reduced from duck manure by adding reed straw [24]. Many researchers are working on several composting methods in recent years, such as biochar being used as a bulking agent to convert organic waste into carbon-rich sources [25–27]. However, there is still a lack of knowledge about vermicomposting with biochar and the role of earthworms without any other manure.

Vermicomposting is a mesophilic process in which microbial activities exhibit aerobic conditions leading to ammonia volatilization and GHG gases (CO_2, CH_4, and N_2O) emissions as well [28]. Our study in this region hypothesized that better management of organic waste materials (manure and crop residues) by an ecofriendly technique can provide nutrient-rich organic fertilizer for agricultural use to avoid environmental pollution.

The study's primary objectives were to study (1) nutrient enrichment during the vermicomposting process, (2) ammonia volatilization during vermicomposting of animal manures and biochar, and (3) effective vermicomposting substrate with less environmental loadings.

2. Materials and Methods

2.1. Study Site

The field vermicomposting experiment was established at Yanting Agroecological Experimental Station, which is a member of the Chinese Ecosystem Research Network (CERN), Chinese Academy of Sciences, located 31°16′ N, 105°28′ E at an altitude of 530 m in the Sichuan Basin, China. Climatic conditions of the area are subtropical monsoon, and the average annual temperature is 17.3 °C, while average annual precipitation is 836 mm. Location of study site and the climatic conditions (monthly minimum and maximum air temperature and rainfall) during the experimental vermicomposting are shown in Figures 1 and 2, respectively.

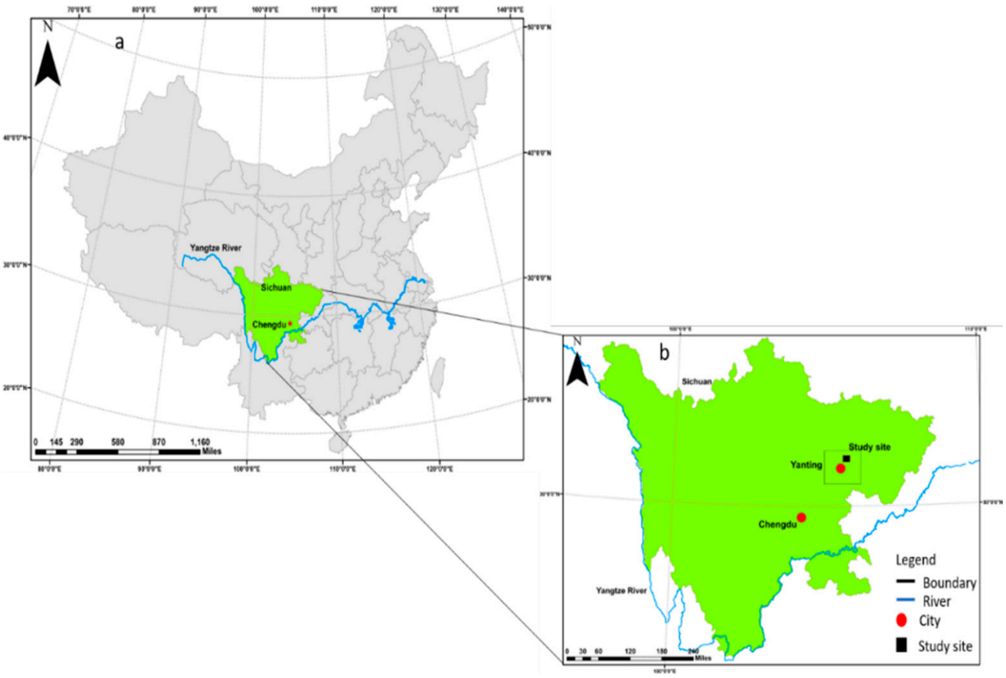


Figure 1. Location of study site.

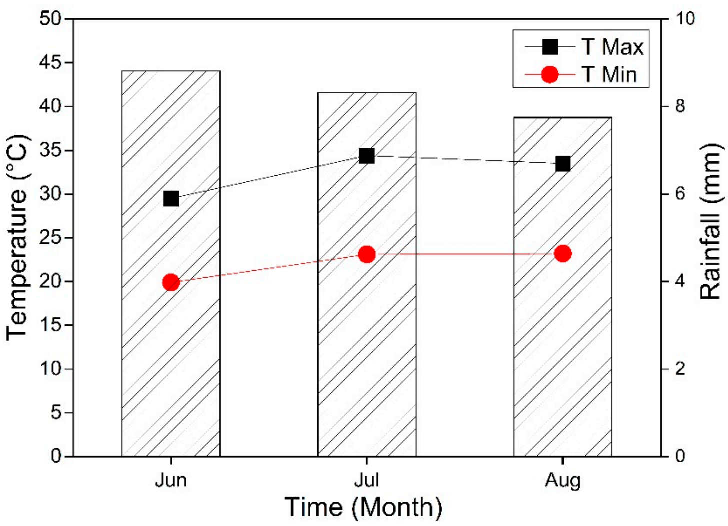


Figure 2. Climatic conditions during the experimental period.

2.2. Waste Materials for Vermicomposting

Crops (wheat straw and rapeseed) residue and animal (cow and pig) manures were collected from breeding farms near the study site. Earthworms (*E. fetida*) were managed from the sellers, while biochar was purchased from Sanli New Energy Company at Shangqiu, Henan, China. Biochar was produced from one ton of crop straws by slow pyrolysis at 500 °C in a fluidized bed furnace on a scale of 1000 t day^{-1}. One ton of crop straw yielded 0.3 t of biochar, with coproducts including 0.25 t pyroligneous acid, 0.03 t wood tar, and 780 m^3 gases. The particle size distribution of the biochar is not uniform, consisting of 38% of <0.25 mm fraction, 38% of 0.25–1 mm fraction, and 24% of 1–3 mm fraction, respectively. The raw biochar concentrations of total nitrogen TN 10.4 ± 0.8, total organic carbon TOC 446.8 ± 15.1, total phosphorus TP 1.95 ± 26, total potassium TK 32.6 ± 7.2 (g kg^{-1}), and C: N 42.95 ± 3.7.

2.3. Experimental Setup

The field experiment was set up for two months for current research, with four treatments to monitor the dynamics of macro- and micronutrients and emissions of gases with and without earthworms. Four treatments were prepared in the form of triplicates, with a total of 100 kg of waste materials on dry weight basis using 70% (seven portions) crop residues (wheat straw 50% and rapeseed 20%) and 30% (three potions) manures. In contrast, 30% of biochar was used as an alternative substrate, instead of manure in one treatment (VBC). Waste materials were mixed with seven portions of crop residues and three portions of cow dung (VCM), pig manure, and biochar (VBC), respectively, in plots with 2 × 1.5 × 0.6 m in length, width, and height, respectively. The plots contained 15 cm of purplish soil layer with its unique physical and chemical properties [29].

After mixing, all plots were covered with a net, and proper aeration was ensured. Five hundred *Eisenia fetida* were added in three treatments (excluding COM, taken as control treatment) after two weeks. During the experimental period, water was added every twenty days for maintaining moisture around 60–70% to keep conditions favorable for earthworms. On the same day, samples were also collected for analyses.

2.4. Physiochemical Properties and Nutrients Analysis

Compost samples were analyzed for pH and electrical conductivity (EC) with 1:10 aqueous suspension [30]. Total organic carbon (TOC) was analyzed as a dried form, and total nitrogen (TN) concentration was also obtained by running samples in an Elementar Analysensysteme Gmbh. In the laboratory, 25 mL of a 0.5 M $K_2Cr_2O_7$ solution was used for samples (5 ± 0.5 g), after which 0.45 µm membranes were used to filter the supernatant. Following this, an Auto Analyzer-AA3 (Bran+ Luebbe, Norderstedt, Germany) was used to analyze the NH_4^+-N, NO_3^--N, and dissolved organic carbon (DOC) contents in the filtrates.

For further analysis of total phosphorus (TP), 2 g of dried samples were prepared for phosphorus extraction [31], and digested with 10 mL diacid ($HClO_4$: HNO_3 with 1:5 ratio). The volume of the digest was made up to 100 mL and filtered through Whatman No. 1 filter paper. A flame atomic spectrophotometer (Thermo Scientific, iCE 3000 SERIES, UK), was used to analyze nutrients: total potassium (TK), total calcium (TCa), total magnesium (TMg), total manganese (TMn), total copper (TCu), total iron (TFe), and total zinc (TZn) concentration in the samples.

2.5. Measurement of Ammonia Volatilization

Ammonia volatilization was measured using the small static, dynamic flow cylindrical chamber method [32], and NH_3 flux was calculated by the method of Cao et al. [33]. The chamber was inserted into waste materials for composting and vermicomposting at a depth of 5 cm. The chamber was made of poly-methyl methacrylate with a 20 cm inner diameter and 10 cm height. A vacuum pump was connected with polyvinyl pipes for exchange with ambient air at the height of 2.5 m with a flow rate at

10 min^{-1} through the chamber. Then, NH_3 in glass bottles was trapped using acid trap containing 80 mL of concentrated sulfuric acid solution. The gas samples were collected twice per day in the first week for two hours, from 8–10 a.m. and 5–7 p.m., while in the second week, only once a day. The frequency was changed to two times per week after the addition of earthworms. Hourly fluxes per samplings were converted to calculate per day emissions. The cumulative NH_3 loss was calculated from each treatment by summing NH_3 volatilization at each sampling day. The ammonium nitrogen (NH_4-N) in the acid trap was titrated with a 0.01 $molL^{-1}$ standard diluted sulfuric acid solution. The NH_3 volatilization was determined with flow injection auto-analyzer and calculated using the following formula:

$$F = \frac{2 \times C \times V \times 14 \times 10^{-2}}{\pi \times R^2} \times \frac{24}{t} \tag{1}$$

where F is the total flux of NH_3 volatilization (kg N ha^{-1} d^{-1}), and C represents sulfuric acid (mol L^{-1}), V is the volume consumed as standard diluted H_2SO_4 (ml), t is the duration of collection (h), and R is the chamber radius (m). For the cumulative NH_3 losses, the sum of all volatilization fluxes was done on sampling days.

2.6. Measurement of Greenhouse Gas Emissions

The measurements of CO_2, N_2O, CH_4 were conducted by static chamber gas chromatography technique [29]. For this purpose, the 50 × 50 cm stainless-steel chamber was introduced into the 10 cm deep compost. The 50 cm height chamber was fully wrapped by an insulating sheet to reduce the chances of temperature changes during gas sampling from inside to outside the chamber. The samples were measured at daily intervals for the first week, and then frequency was changed to one day gap, later twice per week for the remaining weeks. Five samples were taken in the field after every seven minutes with 60 mL syringes. These syringes were attached with closed chambers by 3-way stopcocks through the Teflon tube. During gas sampling, the temperature inside the chamber and a manual thermocouple thermometer also determined compost temperature. The samples collected were carried to the laboratory, where a gas chromatograph (HP-5890 Series II, Hewlett- Packard Alto, GC, California, USA) was fitted to an electron capture detector (ECD) for analysis. CO_2, CH_4, and N_2O fluxes were detected from linear or nonlinear values as increased, selected based on r^2 values in their headspaces with time, and considering, along other parameters, the headspace height of the chamber, temperature, and pressure of the air. The method of Zheng et al. [34] was used to measure greenhouse gas emissions on sampling days. The cumulative gases emissions were determined by the following equation [35]:

$$C = \frac{\sum F_{i+1} + F_i}{2} \tag{2}$$

where C represents cumulative emission, F is flux, i expressed as the initial day of sampling, and t is time duration (h), sample collection the experiment. The sum of all fluxes was taken according to the sampling frequency for all cumulative emission of gases.

Calculation of global warming potential (GWP) was also made to evaluate total global warming effects for CO_2, CH_4, and N_2O emissions. During the whole experimental period, the GHG emissions were transformed to CO_2-equivalent and summed to get total GHG discharges as warming potential (for 1 mol CH_4 = 34 mol CO_2-equivalent) and (for N_2O = 298 mol CO_2-equivalent).

2.7. Statistical Analyses

The differences of an experimental setup for different parameters and nutrients were tested through one-way analysis of variance (ANOVA) among all treatments ($p < 0.05$). For all nutrients, a difference within the group was found to be significant, and the least significant difference using Tukey's test was used to explain particular treatment for gas emissions. Data were analyzed using SPSS software 15.

3. Results and Discussion

3.1. EC and pH during Vermicomposting

The pH decreased from initial to final values during experimental duration in COM (7.99 to 7.11), VCM (7.44 to 7.14), VPM 7.61 to 7.07), and VBC (7.48 to 6.95), respectively (Figure 3a). Electrical conductivity also decreased in all treatments from initial to final values in COM (7.99 to 2.19), VCM (7.74 to 2.19), VPM (7.61 to 2.24), and VBC (7.48 to 2.6), respectively (Figure 3b).

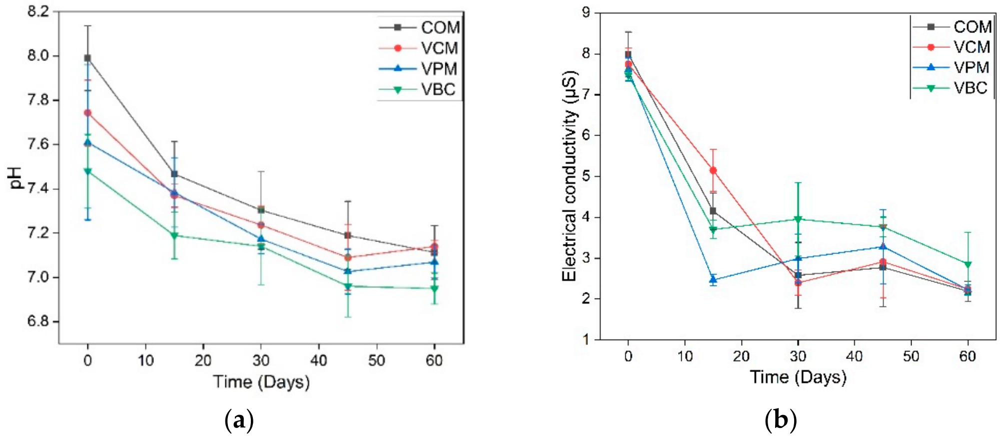


Figure 3. Temporal variations in (**a**) pH and (**b**) electrical conductivity during vermicomposting. Error bars represent standard errors ($n = 3$).

The reasons for decrease in pH during vermicomposting are decomposition of organic matter [36], CO_2 emissions due to organic acid production [37], and presence of NH_4^+-N ions and humic acid [38]. Similar trends for EC were also observed and the decrease might be due to the utilization of soluble salts by microorganisms for the synthesis of microbial biomass, and also due to the absorption of soluble salts by earthworms and enhanced microbial activities [30].

3.2. Macronutrients during Degradation Processes

The TOC contents decreased to 319.2 (COM), 276.00 (VCM), 298.68 (VPM), and 382.20 (VBC) from their initial values of 385.58, 373.81, 376.99, and 390.55 g kg^{-1}, respectively. All treatments showed significant difference of TOC change within groups ($p < 0.05$). In Table 1, the maximum decrease (26.16%) was observed in VCM while a minimum decrease was observed in VBC (390.55 to 382.2 g kg^{-1}). Similar results were also documented by Manyuchi et al. [39]. The reduction in carbon content could be due to loss of CO_2 owing to the activity of earthworms with microbial respiration [40]. In the soil medium, the addition of biochar might cause an increase in the retention of nutrients such as C and N [26,41–44].

Total nitrogen (TN) is an essential nutrient for plant growth. In our study, all treatments showed a substantial increase from its initial contents, as shown in Table 1. The statistically significant difference was shown within the treatments ($p < 0.05$). The maximum increase of (64.04%) nitrogen content was observed in VCM (17.7 to 29.15 g kg^{-1}). The percent increase in nitrogen was minimal in VBC (0.11%) (Table 1), and it was found to be significantly different from VPM ($p < 0.05$). Nitrogen is considered an essential building block of amino acids, leading to increased mineralization of plant residues and conversion into ammonium nitrogen [40]. Composting through pig manure was an adequate nitrogen source as also documented by various researchers [45–47]. The pig manure-based vermicompost triggered a significant increase in nitrogen content [48,49]. These results may contrast with other studies due to differences in selected earthworm species, burrowing, and feeding behavior [50].

Table 1. Initial and final nutrient contents (g kg^{-1}) within treatments.

Treatments	COM		VCM		VPM		VBC	
Nutrients	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
TOC	385.24 ± 1.0	319.25 ± 1.4 ^{ab}	373.81 ± 0.9	276.00 ± 2.0 ^{b}	376.99 ± 1.9	298.68 ± 4.6 ^{b}	390.55 ± 2.0	382.20 ± 2.5 ^{a}
TN	13.78 ± 0.4	22.49 ± 0.2 ^{a}	17.77 ± 0.4	29.15 ± 0.0 ^{ab}	20.15 ± 0.2	26.62 ± 0.3 ^{a}	17.51 ± 0.1	17.53 ± 0.2 ^{b}
TP	1.79 ± 0.2	3.37 ± 0.2 ^{b}	3.26 ± 1.0	3.41 ± 0.3 ^{b}	2.21 ± 0.8	7.74 ± 0.3 ^{a}	2.92 ± 1.7	2.20 ± 0.0 ^{c}
TK	8.14 ± 3.9	11.24 ± 4.0 ^{a}	9.21 ± 4.0	13.77 ± 2.0 ^{a}	10.29 ± 3.3	12.10 ± 2.2 ^{a}	14.46 ± 2.9	14.01 ± 4.0 ^{a}
T Ca	4.30 ± 0.6	26.60 ± 4.9 ^{a}	9.14 ± 0.1	29.75 ± 4.0 ^{a}	16.78 ± 2.0	46.71 ± 7.1 ^{a}	17.83 ± 3.0	35.42 ± 1.9 ^{a}
T Mg	2.58 ± 1.0	4.97 ± 1.0 ^{b}	2.72 ± 0.7	5.26 ± 0.2 ^{ab}	4.74 ± 0.5	7.86 ± 1.3 ^{a}	3.85 ± 0.5	6.73 ± 1.3 ^{ab}
T Cu	0.06 ± 0.0	0.03 ± 0.0 ^{b}	0.02 ± 0.0	0.03 ± 0.0 ^{b}	0.25 ± 0.1	0.38 ± 0.1 ^{a}	0.02 ± 0.0	0.03 ± 0.0 ^{b}
T Fe	2.01 ± 1.0	3.76 ± 0.1 ^{a}	1.98 ± 0.8	3.77 ± 0.3 ^{a}	1.81 ± 0.2	3.74 ± 1.0 ^{a}	3.22 ± 0.0	4.05 ± 1.9 ^{a}
T Mn	0.16 ± 0.1	0.27 ± 0.0 ^{b}	0.09 ± 0.0	0.26 ± 0.0 ^{b}	0.12 ± 0.0	0.36 ± 0.0 ^{a}	0.12 ± 0.0	0.20 ± 0.0 ^{c}
T Zn	0.04 ± 0.0	0.03 ± 0.0 ^{b}	0.01 ± 0.0	0.04 ± 0.0 ^{b}	0.21 ± 0.0	0.37 ± 0.0 ^{a}	0.01 ± 0.0	0.03 ± 0.0 ^{b}
C:N ratio	22.03 ± 5.8	14.9 ± 1.3 ^{c}	22.13 ± 6.2	14.47 ± 0.1 ^{b}	18.79 ± 1.1	14.47 ± 0.1 ^{b}	23.84 ± 4.0	22.73 ± 4.5 ^{a}

Note: The mean values of three replicates after "±" signs show standard deviation (n = 3). Different letters indicate significant differences among treatments ($p < 0.05$). Four treatments, COM (compost without earthworms), VCM (using cow manure), VPM (through pig manure), and VBC (using biochar), were applied with agricultural wastes such as rapeseed and wheat straw in combination with cow dung, pig manure, and biochar, respectively.

Total phosphorus (TP) increased with time except VBC (minimum increase in VCM). In contrast, the maximum increase in VPM (2.21 to 7.74 g kg^{-1}) was observed (Table 1), but a nonsignificant difference was observed between VPM and the other three treatments ($p < 0.05$). The maximum two-fold increase of phosphorous contents was recorded in VPM (Table 2). Lazcano and Dominguez [51] also described an upsurge in phosphorus content while using pig manure for vermicomposting. Similar results by Dass et al. [52] concluded that maybe it can be attributed to phosphorylation of organic content due to the presence of earthworms in cow dung [53]. The maximum increase in total potassium (TK) content was (49.51%) in VCM treatment while VBC showed no significant difference between treatments ($p > 0.05$). Different TK level was ascribed to the decomposition of organic content by *Eisenia fetida* that converted insoluble potassium to soluble TK [6].

Table 2. Nutrients increase or decrease (%) in all treatments.

Treatment	**COM**		**VCM**		**VPM**		**VBC**	
Nutrients	**Increase**	**Decrease**	**Increase**	**Decrease**	**Increase**	**Decrease**	**Increase**	**Decrease**
TOC		17.12		26.16		20.77		2.13
TN	63.20		64.04		32.10		0.11	
TP	88.22		4.60		250.2			24.65
TK	38.08		49.51		17.58			3.11
T Ca	518.60		225.49		178.36		98.63	
T Mg	92.63		93.38		65.82		74.80	
T Cu		50	50		52		50	
T Fe	87.06		90.40		106.62		25.77	
T Mn	68.75		188.88		200		75.32	
T Zn		25	300		76.19		200	
C:N ratio		32.36		34.61		22.99		4.65
C:P ratio		56		29.41		77.33	29.88	

The carbon to nitrogen ratio showed a similar trend, as the carbon percentage was observed to significantly decrease in VCM ($p < 0.05$) (Table 1). The largest decrease in C:N ratio was 34.61%, as shown in Table 2. VBC and VCM were significantly different than COM ($p < 0.05$). Reduced C:N ratio is helpful in plant growth and increasing fertility of the soil. The increased C: N ratio becomes problematic for earthworms to extract an adequate amount of nitrogen for their tissue production [54]. A significant difference in VCM and VBC was observed in carbon. At the same time, VBC was statistically different from other treatments in the C: N ratio, which also reduced the emission of gases during vermicomposting treatments.

The carbon to phosphorus ratio is also an essential aspect of the degradation process during composting and vermicomposting. The maximum decrease (77.3%) was observed in the VPM of the

C:P ratio in our study (Table 2). A highly rapid decomposition of organic matter was also achieved in all VC treatments, in contrast with COM. The results also confirmed the quick breakdown and mineralization of animal waste materials using earthworms [55].

3.3. Micronutrients during Degradation Processes

There was an overall increase in total calcium in the series COM > VCM > VPM and VBC, but the difference among concentrations in treatments was not statistically significant, raised to five fold, two folds, and one fold, respectively. The total magnesium concentration also significantly increased in all treatments without any significant difference between treatments. Likewise, TMg enrichment in VCM showed increase (93.38%) noted in Table 2, while at the end of vermicomposting duration in VPM, Mg contents were 7.86 ± 1.3 g kg^{-1}, as shown in Table 1. In the current study, total calcium contents were also increased as it is an essential nutrient for plant growth and for regulating cell signal pathways [56].

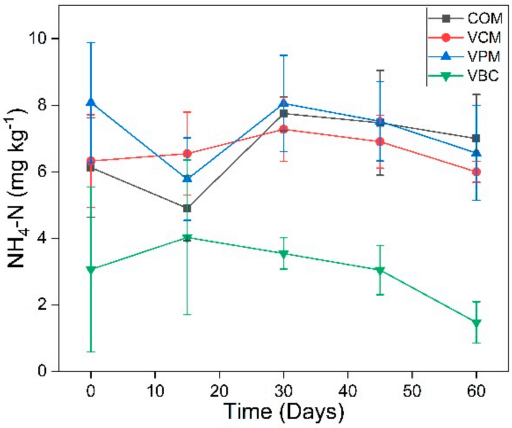
The increase of total Mg in all vermicomposting treatments is attributed to the mineralization of organic matter [57]. The TMg content, which increased in our study of vermicomposting, supported similar results with vermicomposting of sewage sludge [58].

The total copper contents increased in all vermicomposting treatments while it decreased in COM. The maximum increase was observed in VPM (52%) with a statistically significant difference emphasis in concentration as compared to COM ($p < 0.05$), while VCM showed an increase (50%). The maximum iron contents increased in VPM (3.74 ± 1.0 g kg^{-1}), then VCM (93.38%), as shown Tables 1 and 2, respectively. TMn contents increased in all treatments, order as VPM > VCM > VBC and COM at the end of the experimental duration, as described in Table 1. TZn contents also showed an increase in vermicomposting treatments except for a reduction in COM. The overall increase in total ferrous, total manganese, and total zinc contents were observed in all treatments, and similar trends for trace elements were recorded by Pattnaik and Reddy [59]. The highest concentration was recorded in VPM. There was no significant difference among treatments in the case of manganese and ferrous iron, but significant difference was observed in VPM and COM ($p < 0.05$). An increase in these elements with time is attributed to earthworms' catabolic activity on carbonic anhydrase found in calciferous glands of worms [60]. El-Haddad et al. [61] suggested that earthworms can convert the consumed organic content into equal amounts of vermicast as per their body weight. According to Dortzbach [62], pig manure substantially increased the manganese, copper, and zinc accumulation in soil, similar to the current research. The aggregation of zinc and copper is also in line with the findings of L'Herroux et al. [63]. Earthworms' addition in vemicompost not only enhanced the levels of NPK, but also the micronutrients such as iron, manganese, zinc, and copper [64]. Addition of earthworms with different substrates (cow manure, pig manure, etc.) increases the microbial growth as well as mineralization of soil nutrients that increases fertility and quality of soil [65–67].

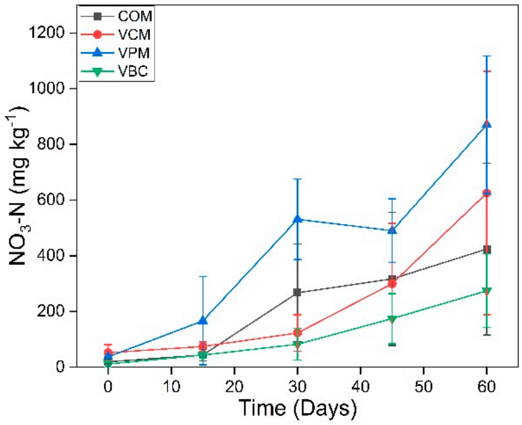
All the treatments were compared statistically between the treatment, and the analysis showed a significant difference in the case of all nutrients ($p < 0.05$) except for some micronutrients such as total calcium and ferrous iron. The initial and final nutrient contents are given in Table 1.

3.4. Dynamics of Nitrogen and Carbon Forms

The trends of ammonium nitrogen (NH_4-N) contents in all treatments are shown in Figure 4a and trends of nitrate nitrogen (NO_3-N) contents and dissolved organic carbon during the decomposition period of all treatments are shown in Figure 4b,c, respectively. All the treatments showed increasing values from its initial phase.



(**a**)



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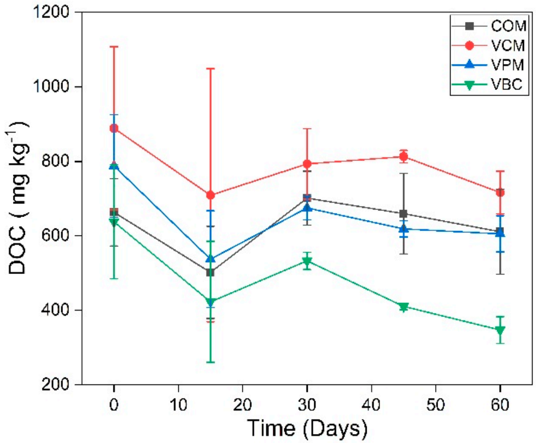


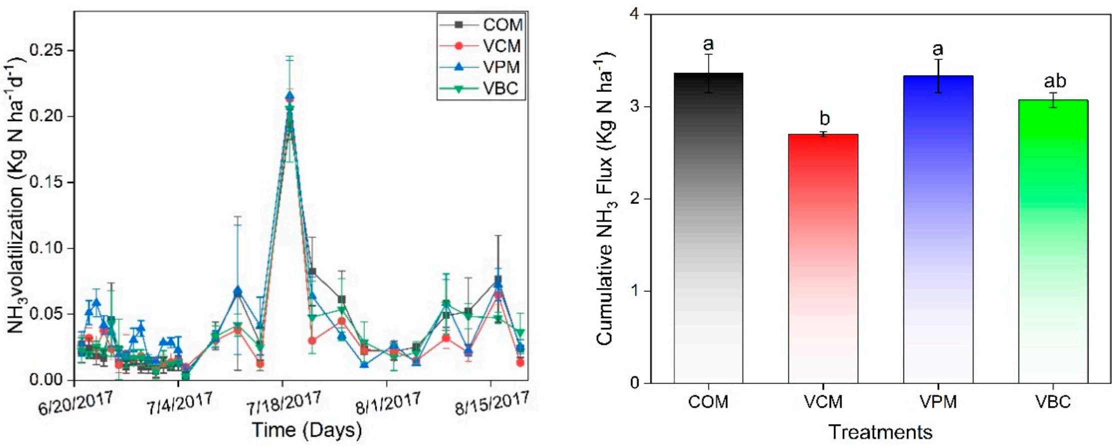
(**c**)

Figure 4. Mineral forms of nitrogen: NH_4-N content (**a**), NO_3-N content (**b**), and dissolved organic carbon (**c**) in all treatments as a mean of three replicates; error bars represent standard errors (n = 3).

Although an overall decreasing trend was observed in ammonia, although the slight increase in VCM can be due to earthworm casts in higher amounts [68] and quick mineralization processes, resulting in enhanced ammonification [25]. The nitrate contents increased in all treatments, and vermicomposting showed a greater increase than composting, which reflected the conversion of ammonia into nitrate by oxidation through nitrifying bacteria [69]. The changes in DOC were decreased due to the degradation process. The moisture content might be enhancing DOC after the initial decrease but later decreased. The decreasing DOC trend is in line with Wang et al. [36].

3.5. NH_3 Volatilization

Ammonia volatilization was higher in the early period in composting and all three vermicomposting treatments (Figure 5a). The mixing of compost piles also enhanced the NH_3 emissions. The peaks were observed after mixing the first interval of 20 days, and earthworm activities also showed high emissions due to increased temperature. VPM showed higher emissions in initial days as compared to other treatments. The cumulative ammonia flux in COM, VCM, VPM, and VBC were evaluated as 3.36, 2.70, 3.33, and 3.06 kg N ha^{-1}, respectively (Figure 5b). The COM showed a significant difference from VCM ($p < 0.05$). VCM emitted about 3.3 kg N ha^{-1}, which is significantly lower than VPM among vermicomposting treatments while showing significantly lower than COM. Composting with biochar amendment reduced nitrogen loss [70], and VBC clearly showed that vermicomposting with biochar also reduced NH_3 volatilization. Differences of NH_3 volatilization could be explained by the physical and chemical properties of different substrates exhibiting dissimilar temperature and moisture [71] (Table 2). During pre-composting, the emissions may have occurred due to ammonium nitrogen contents in raw composted materials, then decreased gradually during the observation period.



(**a**) (**b**)

Figure 5. NH_3 volatilization (**a**) and cumulative NH_3 flux (**b**) in all treatments of three replicates. Error bars represent standard errors. Different letters indicate significant differences among the treatments ($p < 0.05$).

Lv et al. also reported the mixing of compost piles for better aeration caused an increase in NH_3 volatilization in different time intervals and the same trend [72]. The decreasing trend of NH_3 loss in composting resulted from increased temperature, which made the material easily degradable, and this phenomenon is described well by Awasthi et al. [25]. NH_3 emission results emphasized that vermicomposting of all treatments with cow dung (VCM) have lower loading compared to traditional composting.

3.6. CO_2, CH_4, and N_2O Emissions

The dynamic emission of greenhouse gases (GHG) during the degradation of organic waste materials was observed. The CO_2 emissions with the highest peak in VPM on day-four after compost piles were well-mixed are shown in Figure 6a. The cumulative fluxes show a significant difference between the treatments ($p < 0.05$). The cumulative fluxes (Figure 6b) in all treatments, COM, VCM, VPM, and VBC, were evaluated as 842.3, 1072.6, 778.5, and 751.4 g C m^{-2}, respectively. COM was significantly higher than VPM ($p < 0.05$). VCM emitted higher fluxes, among vermicomposting treatments other than composting.

The CH_4 emissions were higher in VPM (Figure 6c) before compost piles were well-mixed, and moisture concentration was low during the first three days. The difference was nonsignificant for cumulative fluxes between the treatments. The cumulative fluxes (Figure 6d) in all treatments COM, VCM, VPM, and VBC, were evaluated as 0.35, 0.33, 3.63, and 0.11 g C m^{-2}, respectively. The VBC is significantly lower than the VPM ($p < 0.05$). The COM was significantly higher than VPM ($p < 0.05$). The higher fluxes in VPM were observed among other vermicomposting treatments. The CH_4 emissions during vermicomposting treatments could be attributed to earthworms functioning as ecological engineers for aeration because of their burrowing activities, which decreased the cumulative methane emissions due to the large quantity of methanogen *Methanosarcina* in cattle [73].

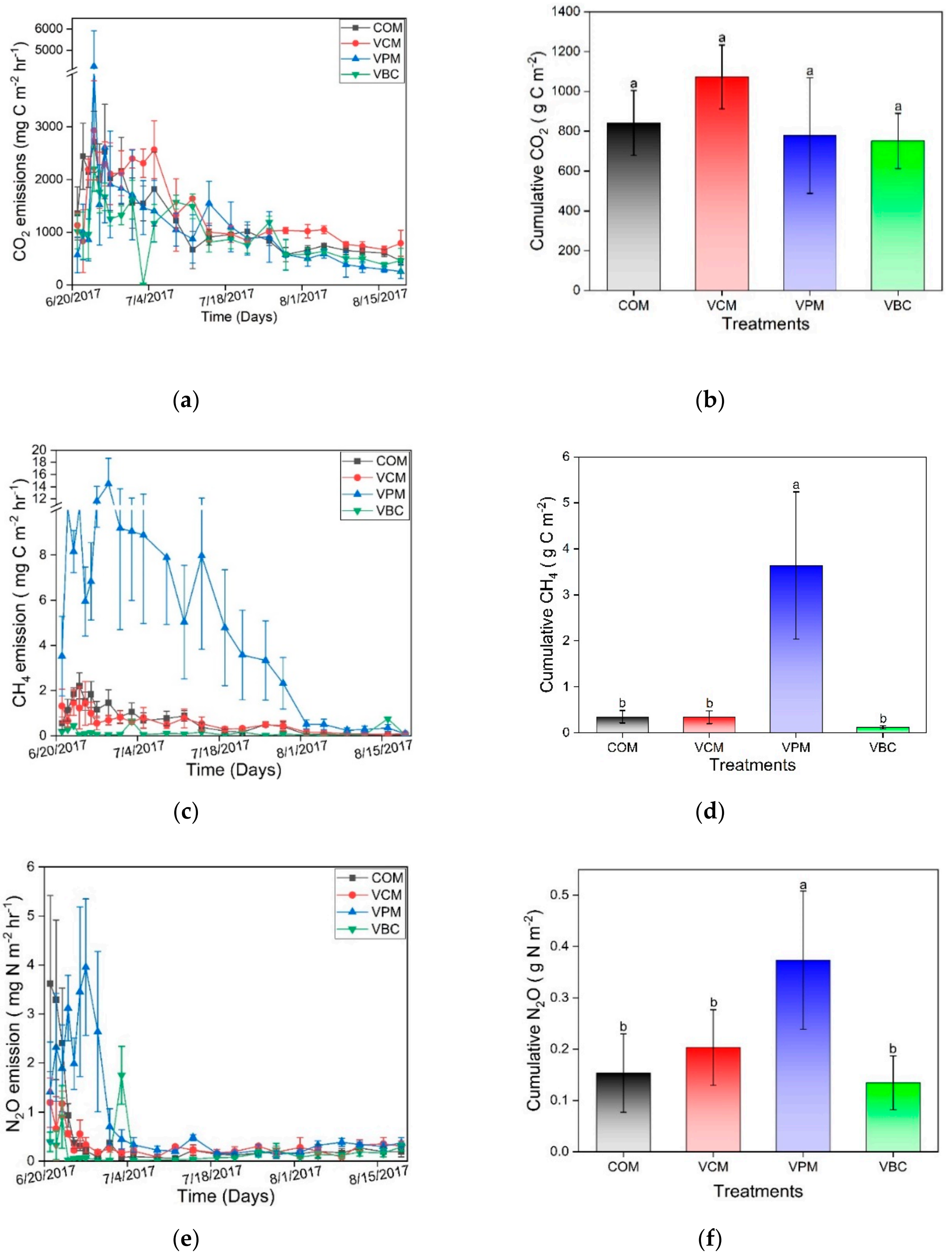


Figure 6. (**a**) Carbon dioxide emissions, (**b**) cumulative carbon dioxide, (**c**) methane emissions, (**d**) cumulative methane emissions, (**e**) nitrous oxide emissions, and (**f**) cumulative nitrous oxide emissions in all treatments for the whole experimental duration as mean of three replicates. Error bars represent standard errors. Different letters indicate significant differences among the treatment ($p < 0.05$).

The high peaks of N_2O emissions were observed in the early days of the experimental period, particularly before well-mixed compost piles, as shown in Figure 6e. The cumulative fluxes show a significant difference between the treatments ($p < 0.05$). The cumulative fluxes (Figure 6f) in all treatments, COM, VCM, VPM, and VBC, were evaluated as 0.15, 0.20, 0.37, and 0.13 g C m^{-2}, respectively. The VPM was significantly higher than COM ($p < 0.05$). The VBC showed a significant difference with VPM ($p < 0.05$). Our results are similar to previous research, which showed that increased emissions in pig manure were due to the elevated threshold availability of nitrogen determined by earthworms [74]. They could also be the result of more substrate (NO_3) in VPC for the denitrification process. The N_2O emissions might be decreased in the presence of earthworms by their gut functioning as anaerobic denitrification [75], which explained the decreased N_2O emissions in VCM and VBC due to their burrowing activities. Furthermore, the change in earthworm production in vermicomposting of the different substrate also made a difference in N_2O emissions compared to the control, as noted in past studies [76], and it could also be due to the more rapid degradation process and the enhanced mineralization process of N [76,77].

Overall evaluation of the vermicomposting practices was considered with high warming potential; two gases CH_4 and N_2O for global warming potential (GWP) have been taken as a sum of gas emissions. VBC treatment had the lowest loadings of GHG emissions.

Considering warming potential, two gases CH_4 and N_2O for global warming potential (GWP), are taken as a sum of gas emissions among all the treatments (Table 3). Using global warming potential GHG, emissions were calculated to range from 3.3 to 16.8 g CO_2-eq/kg. In the vermicomposting process, a transformation of organic wastes by earthworms enhanced the decomposition process and created a nutrient-rich fertilizer by reducing the potential for environmental pollution compared to the traditional composting. The earthworms' presence resulted in better potential for nutrient supply for crop growth and good quality vermicompost, which is very useful for controlling NH_3 volatilization and GHGs emissions compared to the traditional composting method. Compared to composting without earthworms, the vermicomposting treatments resulted in much-improved status in most of the nutrients (Table 1). Additionally, both vermicomposting with cow dung and pig manure were encouraged by previous studies [69].

Table 3. Total greenhouse gases (GHG) emissions and global warming potential (GWP) in all treatments.

Treatments	GHGs Emissions Equivalent (g CO_2-eq/kg)			
	CO_2	CH_4	N_2O	GWP
COM	92.3	0.01	0.01	3.32
VCM	118.1	0.01	0.02	6.3
VPM	85.7	0.14	0.04	16.8
VBC	82.7	0.01	0.01	3.3

4. Conclusions

This study showed that vermicomposting significantly enhanced macro and micronutrient status. VCM can be regarded as a better treatment than composting during ammonia volatilization, but VPM provided maximum beneficial nutrient retrieved. VCM showed better results in increasing nitrogen and decreasing both carbon and C:N ratio. High nitrogen and low C:N ratio ensured the good quality of the compost. VPM provided increased nutrient contents from its initial to final values, but the greenhouse gases emissions were significantly higher than other treatments. VCM and VPM are recommended to increase the plant growth for an increasing nutrient profile.

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