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Impacts of vermicompost application on crop yield, ammonia volatilization and greenhouse gases emission on upland in Southwest China

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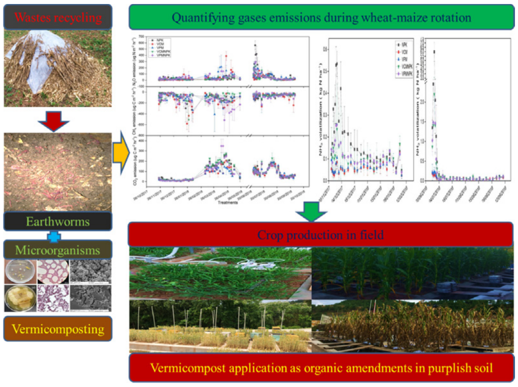
HIGHLIGHTS

- NH_3 volatilization was reduced under the application of cow and pig manure vermicompost.
- GHG emissions and GWP under vermicomposting
- The use of vermicompost fertilizer increased crop yield by 5 %.
- Evaluated nutrients stabilization during wheat-maize cropping system in purplish soil.
- Vermicomposting as an eco-friendly farming practice in the subtropical region.

GRAPHICAL ABSTRACT



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ABSTRACT

Ammonia (NH_3) volatilization and greenhouse gas (GHG) emission are important environment pollution sources in upland agro-ecosystems. Vermicompost was used for amending purple soil and comparing NH_3 and GHG emissions. A field experiment was conducted with a comparison of organic and inorganic fertilizers in a wheat–maize rotation system in the Sichuan Basin, China. The five treatments were conventional inorganic fertilizers, NPK as control; vermicompost prepared with cow dung (VCM); and pig manure (VPM); cow dung and pig manure vermicompost, respectively (VCMNPK, VPMNPK). Total nitrogen rates of all treatments were the same. Soil NH_3 volatilization and GHG emissions were monitored with the static chamber method. The results showed that NH_3 volatilization occurred in the first two weeks following nitrogen (N) fertilization. The cumulative fluxes of NH_3 recorded in the NPK, VCM, VPM, VCMNPK, and VPMNPK treatments were 15.4, 5.7, 6.3, 10.32, and 10.29 kg N ha^{-1} yr^{-1}, respectively, in the winter and 4.8, 5.5, 19.83, 12.8, and 11.9 kg N ha^{-1} yr^{-1} respectively, in the summer. The global warming potential (GWP) 773.6 and 803.9 g CO_2-eq m^{-2} in VCM and VPM, respectively, during the wheat season 540.6 and 576.2 g CO_2-eq m^{-2}, respectively, during the maize season. The GWPs in NPK treatment were 1032.4 and 570.7 g CO_2-eq m^{-2} during the wheat and maize seasons, respectively. The increasing effects of nutrient loops, particularly 18 % soil total nitrogen (TN) and 31 % soil organic carbon (SOC) in VCM, and crop productivity of vermicompost treatments during the wheat–maize rotation had been evaluated. This study recommends that VCM can be considered as a better organic amendment, promoting plant growth while decreasing the environmental costs of gas emissions.

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1. Introduction

Increased organic waste production owing to the large human population has become a cause of considerable environmental concern. In 2010, the world's population was over 3.1 billion, and that number is estimated to increase to 7.6 billion by 2050 (FAO (Food and Agriculture Organization), 2020; Fair Observer, 2017). The rapid population growth accelerates the demand for food while globally 1.3 billion tons of food are wasted every year (Fao, 2011). The amount of organic waste produced exceeds billions of tons, causing the emission of gases into the soil. Hence, environmentally friendly agricultural techniques are required (Grinsven-van et al., 2022; Thangarajan et al., 2013).

Inorganic fertilizers have been excessively used to meet the food and energy requirements of the world's rapidly growing population. Many types of waste, such as agricultural manure and crop residues, need to be recycled. Hoornweg and Bhada-Tata (2012) reported that large amounts of organic waste were detected in several sources, such as yards, food, and agricultural industries, which produce approximately 46 % of global solid waste. Urea is the most used N fertilizer in agricultural ecosystems (IFA, 2017). N fertilizers are currently extensively used despite the negative effects of excessive amounts of N fertilizers on ecosystems. These effects cause severe environmental problems in soil and water through runoff and leaching and lead to atmospheric pollution and greenhouse gases through N_2O emissions (Zhou et al., 2013). Carbon (C) and N cycles interact when N from manure is mixed with organic carbon in soil. Given that this interaction facilitates soil N retention, it has been explored in many meta-analysis studies (Zhou et al., 2014a, 2015b, 2014c). N cycling, fluxes, and balances in agricultural systems have been investigated by combining synthetic and organic fertilizers, and the use of vermicompost is essential to hypothesis testing and determining mechanisms (Zhou et al., 2018). In agriculture management, raising or maintaining yields while minimizing environmental N loss remains a considerable challenge (Chen et al., 2014). Moreover, comprehensive data on the N budgets of agricultural systems and major fluxes of N are lacking, especially in alternative management practices (Wang et al., 2022; Vitousek et al., 2009).

Vermicomposting is a useful and valuable process in biowaste recycling (Yang et al., 2017). Using earthworms and microorganisms to accelerate the breakdown of organic waste into fertilizer. The earthworm's gut functions as a bioreactor throughout the vermicomposting process, which starts with the ingestion of waste materials. Vermicompost is created as a result of the microbial activity in the worm's gut (Manyuchi and Phiri, 2013), is regarded as an eco-friendly method (Datta et al., 2016: Raza et al., 2019) and an emerging technique (Abbasi et al., 2015) for different substrates and organic fertilizers (Hussain and Abbasi, 2018; Raza et al., 2021a, 2021b; Raza et al., 2022). N is the primary contaminant in several agricultural sites in China, which is the largest consumer of chemical fertilizers in the world. The utilization rate of N fertilizer in China's cropland is only approximately 35 % (Xing and Zhu, 2000). Four pollution sources– livestock, aquaculture, bird feces, and urine– are the most abundant (Huang et al., 2008). The essential contributing element in agriculture systems is a potential fertilizer that contributes to meeting the worldwide food demand (Erisman et al., 2008) while mitigating eutrophication, nitrogen leaching, and emissions of greenhouse gases (IPCC, 2007; Abbasi et al., 2021). In China, regosols (purplish soil) derived their name from Sichuan because of their characteristics of low organic carbon content and color, and they constitute 60 % of croplands (Zhu et al., 2009). In study site, for this research agricultural management for sustaining nutrients and reducing environmental pollution through several pathways has been implemented, and long-term organic amendment strategies have been studied, including organic manure application and combining synthetic fertilizers, crop residues, and other organic substrates (Zhu et al., 2012; Zhou et al., 2013; Gravuer et al., 2019). In this vermicomposting, as a method for reducing pollution in agricultural soils and ensuring sustainable management has attracted considerable interest. Nutrient management involves directly returning crop residues and organic manure, separating synthetic N fertilizers, and mixing them with other organic amendments (Wang et al., 2012; Zhou et al., 2018; Wang et al., 2021a, 2021b). However, the effects of vermicompost as an organic fertilizer for crop production in purple soils have not been fully explored.

The nitrogen cycle is largely controlled by NH_3 losses through volatilization, which account for up to 93 % of N loss annually (Zhou et al., 2016). The terrestrial ecosystem increases the rate of radiation on Earth, causing global climate change (Hauglustaine et al., 2014), and high NH_3 emissions are concentrated in eastern and southwestern China (Kang et al., 2016). N_2O is one of the most concerning greenhouse gases, causing a 20 % increase in pollution in the atmosphere by spreading global radiation (IPCC, 2013). A meta-analysis experiment was conducted for organic amendment using >300 observations and confirmed that animal manure can sustain agricultural productivity by increasing soil organic carbon stocks that influence N cycling and N_2O emissions, and various sustainable methods for environmental effects (Abbas et al., 2019; Hussain et al., 2019; Hussain et al., 2021). Some studies related to CO_2 emissions (Ding et al., 2007) contain crop residues and manure amendments (Wang et al., 2013). In addition to N_2O emissions, Zhou et al. (2015b, a) have discussed CH_4 emissions during nitrogen fertilization in the subtropical region of China. The role of vermicompost application and GHG emissions in upland areas. Nitrate leaching is another N pathway leading to N loss through water and nutrients in the soil. In the quantification of N balance in upland areas, improving sustainable management is important to fulfilling food necessities and quality needs (Zhou et al., 2013). N inputs in agriculture systems accumulate in crops but are lost through various pathways, including hydrological loss and atmospheric gas emissions, and can be comparable (Ju et al., 2009). Nutrient leaching has been explored in detail for organic and inorganic fertilizers in purple soils in the Sichuan Basin of China (Zhu et al., 2009). Zhou et al. (2016) showed that 78 % of annual hydrological N is lost in wheat–maize cropping systems. Differential responses between organic and inorganic amendment have been applied to this region concerning different fertilization regimes affecting N emissions and cycling enzymes (Zhou et al., 2016; Dong et al., 2018; Zhang et al., 2022), but knowledge of vermicompost improvement in N recycling is lacking in upland purple soils compared with synthetic fertilizers. The aim of this study is application of vermicompost in amending purple soil and comparing NH_3 and GHG emissions. The reduction of biological wastes through, reuse by eco-friendly techniques, recycling into agriculture as organic fertilizer, and recovering the nutrients to increase soil fertility and crop production, still require encouraging the use of organic fertilizers (vermicompost and vermicompost combined with NPK) in the agricultural system. The main objectives of this study were to quantify (1) NH_3 volatilization during vermicompost application, (2) GHG gas emissions and N losses during vermicompost application on wheat-maize crop rotation, and (3) agronomic effects and N balance of vermicompost application in upland soil.

2. Materials and methods

2.1. Study site

A field experiment was conducted at Yanting Agroecological Research Station of the Chinese Academy of Sciences, an associated station with the Chinese Ecosystem Research Network (CERN), in the upland areas of purple soil in Sichuan Basin. A moderate subtropical monsoon climate is characteristic, with annual mean precipitation of 826 mm and average annual air temperature of 17.3 °C. At the research station approximately 500 m from the experimental plots, a meteorological station monitored daily precipitation, air pressure, and temperature during the experiment (Fig. 1).

2.2. Experimental design

The site area was used for long-term experiments on organic and inorganic fertilization in cropland. Small field plots (size: 1 m × 1 m) were established and were based on the cropland hydrological way. The purplish soil was partitioned through walls 60 cm in-depth and filled with small

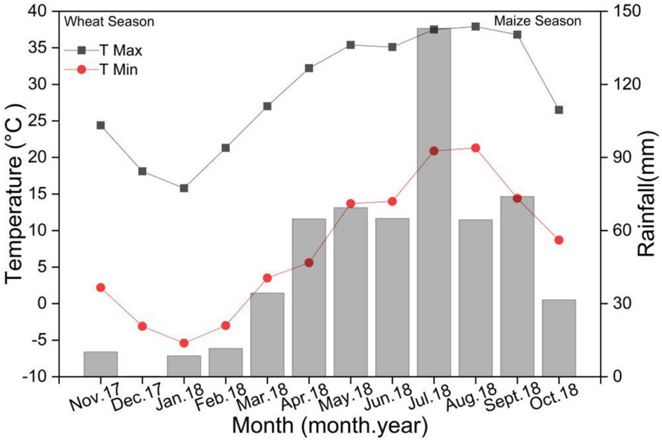

Fig. 1. Climatic conditions during the experimental period of wheat maize crop rotation.

stones and sand as a bedrock to prevent leakage (Zhu et al., 2009). The experimental plots were fertilized at the start of the wheat and maize seasons.

(1) The amount of fertilization was applied at the same N application rate of 280 N ha^{-1} yr^{-1}, 130 N ha^{-1} for the wheat season and 150 N ha^{-1} for the maize season, respectively. All of the N (Urea was used as a synthetic nitrogen fertilizer) and vermpicompost treatments, received the same rates of calcium superphosphate, and potassium chloride supplied with 90 kg P_2O_5 ha^{-1} equivalent, 36 kg K_2O ha^{-1} equivalent, respectively as basal fertilization (Zhou et al., 2016). The organic fertilizers were (2) cow dung vermicompost (VCM; 1.742 TN%), (3) pig manure vermicompost (VPM; 1.713 TN%), and provided the same amount of N as NPK treatment, (4) mixtures of NPK (60 % applied N) cow dung vermicompost (40 % applied N) VCMNPK, (5) mixtures of NPK (60 % applied N) pig manure vermicompost (40 % applied N) VPMNPK, and without any fertilization (CK). The vermicompost with cow manure and pig manure was prepared using waste materials from the same experimental area, experimental details can be find by Raza et al. (2021a, 2021b).

Soil temperature and soil water content were measured in the soil (5 cm depth) during the experiment. Soil temperature and moisture content at 5 cm depth were measured using a manual thermocouple thermometer (JM624, Tianjin Jinming Instrument Co., Ltd., Tianjin, China) and a portable frequency domain reflector probe (RDS Technology Co., Ltd., Nanjing, Jiangsu, China).

2.3. Determination of nutrient contents and physicochemical properties

The TN and total organic carbon (TOC) were measured using a Carbon Nitrogen (CN) Elemental Analyzer (Elemental Analysen Systeme GmbH, Vario M Cube, Germany). The wet digestion method was used in measuring total phosphorous (TP) concentration using a spectrophotometer, the Perkin-Elmer SIMMA 6000 (Lu, 1999). The digestion was done by taking soil samples for each, and was replicated using 10 ml of di-acid ($HClO_4$: HNO_3 in a 1:5 ratio), and the volume of the digest was adjusted up to 100 ml and filtrated using filter paper (Whatman No.1). The total potassium concentration in the sample was measured with a flame atomic spectrophotometer (iCE 3000 SERIES, Thermo Scientific, UK).

2.4. Measurement of ammonia volatilization

A small open static and dynamic chamber method (Guangming et al., 1998) was used in measuring NH_3 volatilization, it had a 20 cm-diameter of inner and 10 cm of height and poly-methyl methacrylate. A vacuum pump was used to exchange ambient air at the height of 2.5 m at a flow rate of 5–10 min^{-1} through the chamber. The circular chamber was inserted into the compost at a depth of 8–10 cm. NH_3 was trapped by the glass bottles through an acid trap containing 50 ml of sulfuric acid solution. The samples were taken twice in a day, everyday for a month in the morning and evening. Then, samples were collected three times a week in the whole experimental duration. Ammonium nitrate (NH_4^+-N) was titrated with 0.05 mol dm^{-3} standard sulfuric acid solution in the acid trap, which was determined calorimetrically with a flow injection autoanalyzer. In this method, NH_3 flux is calculated using the following equation (Cao et al., 2013):

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

F showed total flux of ammonia volatilization (kg N^{-1} ha^{-1} d^{-1}), C represents the concentration of H_2SO_4 (mol dm^{-3}), V is the consumed volume as standard diluted H_2SO_4, t is the duration expressed in hours. By contrast, R is expressed as the radius of a chamber (m). All the volatilization fluxes values were added to get the total NH_3 loss.

2.5. Measurement of greenhouse gas emissions

The CO_2, N_2O, and CH_4 measurements were conducted with static chamber-gas chromatography technique (Zhou et al., 2014a, 2015b, 2014c). The stainless-steel chamber with a 50 cm × 50 cm base was introduced into the 10 cm deep compost. The 50 cm-tall chamber was fully wrapped with an insulating sheet to reduce the chances of temperature changes during gas sampling inside and outside the chamber. The samples were measured at daily intervals for the first week, and then the frequency was changed to alternate days, and then twice a week in the remaining duration of experiment. Five samples were taken for every 7 min with 60 ml syringes. These syringes were attached with closed chambers by three-way stopcocks through the Teflon tube. During gas sampling, internal chamber and compost temperatures were determined with a manual thermocouple thermometer. The collected samples were brought to the laboratory, where a gas chromatograph (HP-5890 Series II, Hewlett- Packard Alto, GC, California, USA) was fitted to an ECD for analysis. CO_2, $CH_{4,}$ and N_2O fluxes were detected from linear or nonlinear values as increased emissions and selected based on r^2 values in headspaces with time. Other parameters, headspace height of the chamber, temperature, and air pressure were considered. The method was used to measure greenhouse gas emissions on sampling days. The cumulative gas emissions were determined by the following equation described by Meng et al. (2005).

$$C = \frac{\sum F_{i+1} + F_i}{2} \times (t_{i+1} - t_i) \times 24 \tag{2}$$

C represents cumulative emission, F is flux, i shows sampling numbers, and t expresses the experiment's start day. The sum of all fluxes was obtained according to the sampling frequency for all cumulative emissions of gases.

The calculation of GWP was used in evaluating total global warming effects for total GHG emissions. The emissions of CO_2, $CH_{4,}$ and N_2O during the whole experimental period were transformed into CO_2- equivalent, summed, and used in calculating total GHG discharges as warming potential (for 1 mol CH_4 = 34 mol CO_2-equivalent) and (for 1 mol N_2O = 298 mol CO_2-equivalent). CO_2 emissions were considered biogenic sources (Mosier et al., 2006; Stocker, 2013; Wang et al., 2014a, 2021b).

Plastic buckets were placed at the outlets of all the plots to collect water samples as leachate (500 ml), which were filtered through a 0.45 mm membrane and assayed for ammonium-N (NH_4^+-N), and nitrate-N (NO_3^--N) concentrations, which contained sediment will be analyzed for total nitrogen concentration before filtration. Suspended sediment and water mixed sample filtrates were analyzed using Auto-Analyzer 3 (SEAL Analytical Ltd., Germany).

2.6. Field crop response measurements and determination of nutrients in the soil

The wheat and maize biomass were determined after crop harvest. All the samples were obtained in triplicates, and the area was 1 m^2. The fresh and dry weight was measured with the usage of oven-dried crops. All the crop parts were treated separately, dried parts of the crops were passed through 0.5 mm sieves, and nutrients were determined in roots, shoots, and grains. An elemental analyzer was used in determining nutrient concentrations.

$$\text{Crop Uptake} = \text{Crop (shoot} + \text{root} + \text{grains)}^{*}\text{Nutrients concentrations (NPK)}$$

The soil samples (0–15 and 15–30 cm depth) were collected from each plot at the bottom position. The soil samples from three random places within plot were mixed for collection of a representative composite soil sample for each plot.

2.7. Statistical analyses

The differences between the experimental setups for different parameters and nutrients were tested through one-way analysis of variance (ANOVA) within treatments and time at the $P < 0.05$ significant level.

3. Results

3.1. Ammonia volatilization

NH_3 volatilization in agro-ecosystems contributes greatly to the quantification of soil fertility and N cycling. Considerable ammonia loss was observedduring the first week of fertilizer application. The highest flux peaks of NH_3 volatilization were observed after inorganic fertilization and then gradually decreased in the first 2 weeks of treatment (Fig. 2a). In this study, vermicomposting has lower emissions than conventional inorganic fertilization used in the purplish soil of the Sichuan Basin. Furthermore, VCM and VPM had lower peaks of NH_3 volatilization flux rates and lower cumulative fluxes than the combined inorganic fertilizers of VCMNPK and VPMNPK. The NPK fertilization showed the highest peaks of NH_3 volatilization in wheat–maize rotation.

The cumulative value of NH_3 volatilization of NPK was considerably higher than the values in VCM and VPM ($P < 0.05$) in wheat–maize rotation seasons and the cumulative values of NH_3 flux in all treatments: NPK, VCM, VPM, VCMNPK, and VPMNPK were 15.4 ± 4.1, 5.7 ± 0.6, 6.3 ± 0.6, 10.32 ± 4.3, and 10.29 ± 4.3 (Kg N ha^{-1}), respectively, in winter, and the emissions were 4.8 ± 0.3, 5.5 ± 1.6, 19.83 ± 5.0, 12.8 ± 2.9, and 11.9 ± 1.1 (Kg N ha^{-1}), respectively, in summer (Fig. 2). The cumulative NH_3 volatilization in VCMNPK and VPMNPK showed higher emissions than VCM and VPM but lower emissions than NPK treatment in the winter wheat season (Fig. 2). Similarly, VCM has the lowest emissions while VPM has slightly higher emissions in the maize summer season than other treatments (Fig. 2).

3.2. GHG emissions under the application of vermicompost

In our study, the application of vermicompost separately and mixed with NPK showed lower N_2O emissions in winter wheat after the incorporation, and gradually increased with temperature. However, in the summer maize season, the temperature during the whole period of experimentation was high, and most of the peaks were observed in the early stages of cropping (Fig. 3). The cumulative N_2O in VPM was 0.16 g N m^{-2} during the wheat season, which was significantly higher than the NPK and

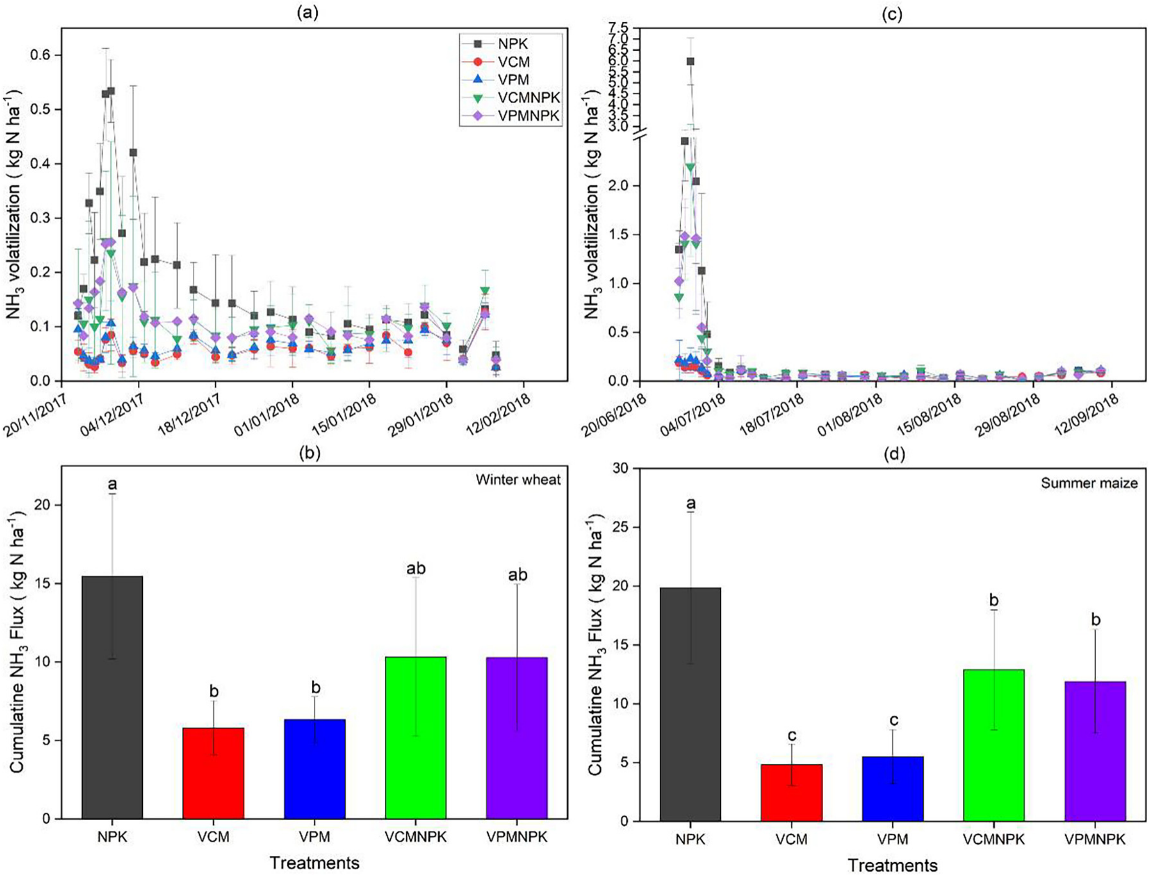

Fig. 2. Ammonia volatilization (a), cumulative NH_3 flux during the winter wheat seasons (b), NH_3 volatilization (c), and cumulative NH_3 flux during the summer maize season (d). Standard errors are represented by error bars ($n = 3$). Significant differences among treatments are indicated by different letters above the columns ($P < 0.05$).

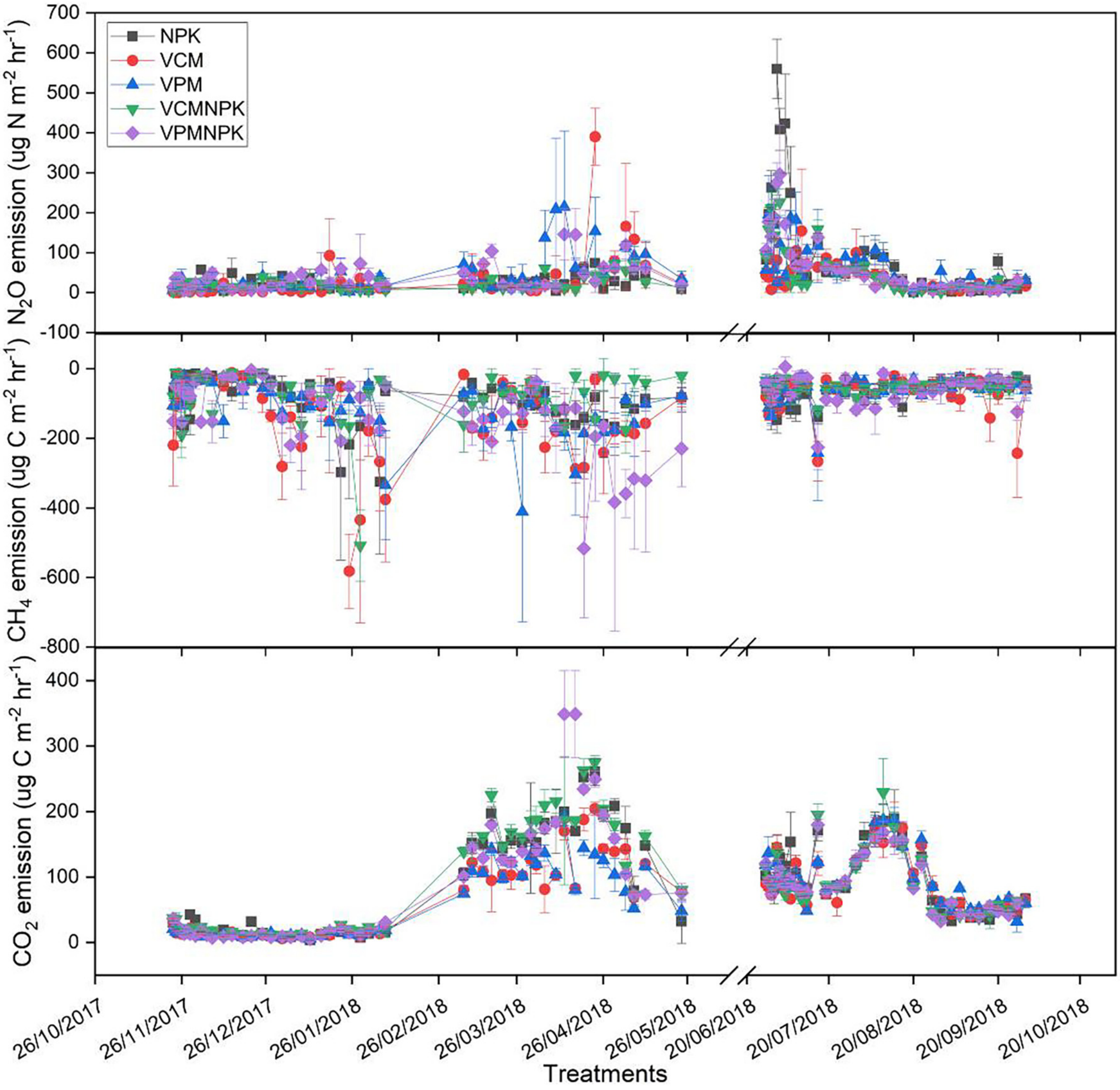

Fig. 3. N_2O emissions (a), CH_4 uptake emissions (b), CO_2 emissions (c) during the wheat and (b) maize seasons. Standard errors are represented by error bars (n = 3).

VCMNPK of approximately 0.06 g N m^{-2}, while VCM and VPM showed significantly low emissions. However, in the maize season, the emissions from VCMNPK, VCM, VPMNPK, VPM, and NPK treatments were 0.051, 0.053, 0.057, 0.079, and 0.084 g N m^{-2}, respectively.

The CH_4 fluctuations after fertilization steadily increased and reached their peaks but still fluctuated with dry and wet conditions (Fig. 3). Changes in CH_4 dynamics were altered as per seasonal in wheat–maize rotation. The CH_4 emissions for the wheat season ranged from −1.277 g C m^{-2} to −0.370 g C m^{-2}, with significantly higher value in the VCMNPK treatment than NPK. In the maize season, the values ranged from −0.432 g C m^{-2} to −0.082 g C m^{-2}. The CH_4 emissions of VPMNPK were higher than those in other treatments in the wheat season (−1.276 g C m^{-2}). The value in the maize seasons was −0.099 g C m^{-2}. The cumulative emissions of NPK, VCM, VPM and VCMPK, were − 0.432, −0.565, −0.471and −0.369, (g C m^{-2}), respectively, in the wheat season. VCM showed the highest cumulative CH_4 uptakes of −0.113 g C m^{-2} in the maize season, and the cumulative emissions of NPK, VPM, VCMNPK, and VPMNPK were − 0.084, −0.091, −0.082, and − 0.099 (g C m^{-2}), respectively.

The dynamic emissions of carbon dioxide (Fig. 3) were lower in the winter season because of the cold climatic conditions. The temperature increased the emissions. CO_2 emissions in the maize season fluctuated and peaked according to dry and wet conditions. In the winter wheat crop, CO_2 emissions ranged from 196 g C m^{-2} to 307 g C m^{-2}. In the summer maize crop, the emissions ranged from 137.43 g C m^{-2} to 148.19 g C m^{-2}. Peaks were observed in vermicompost combined with NPK treatment (VCMNPK and VPMNPK).

The cumulative fluxes for CO_2 in a wheat season were 275, 212, 196, 308, and 278 g C m^{-2} for NPK, VCM, VPM, VCMNPK, VPMNPK, and VCMNPK, respectively. VCM and VPM showed significant decreases in emissions. In the wheat and maize seasons, the fluxes were 142, 143, 137, 146, and 148 g C m^{-2} for NPK, VCM, VPM, VCMNPK, and VPMNPK, respectively. All the treatments showed non-significant differences.

The forms of N-loss nutrients within each treatment are shown in Fig. 4. Organic amendments of vermicompost alone and mixed with NPK exerted positive effects that reduced nitrogen losses. Nitrogen loss through nitrate leaching and runoff was reduced by organic amendments relative to that after inorganic fertilization (Fig. 4). Nitrate leaching showed a significant seasonal pattern, and the highest value was obtained in July, followed by the value in August. value obtained in June.

3.3. Crops responses to different vermicompost

To evaluate the effects of vermicomposting on crop growth, we monitored the grain yield and above-ground and below-ground biomass

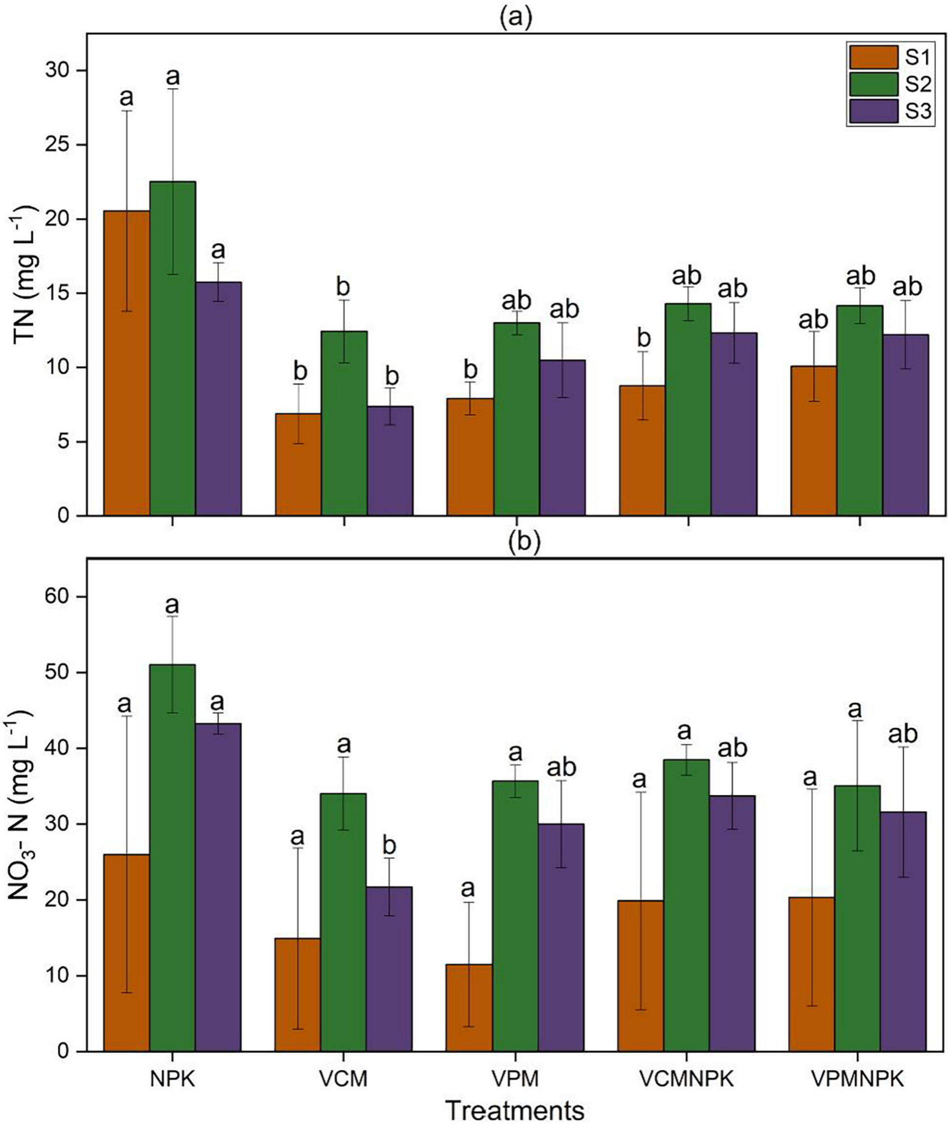

Fig. 4. Seasonal variations in nutrient loss: TN (a), NO_3-N (b), through leaching during wheat-maize rotation. S1, S2, and S3 represent sampling times. Standard errors are represented by error bars (n = 3). Significant differences among treatments are indicated by different letters above the columns ($P < 0.05$).

(Fig. 5). Overall, the grain yields in wheat–maize rotation seasons within treatments were not significant, and the vermicompost treatments showed effects comparable to those of NPK and combined fertilizations, indicating that vermicompost alone can promote crop growth.

To further evaluate the vermicompost effects on the crop nutrients, we measured the carbon (C), nitrogen (N), phosphorus (P), and potassium (K) contents in the grains, shoots, and roots (Tables S1 and S2). No significant difference in crop C content was found among the treatments. Treatments with vermicompost tended to lower the crop N content in comparison with NPK treatment. Crop N uptake ranged from 49 g N m^{-2} to 79 g N m^{-2} in winter wheat and from 106 g N m^{-2} to 160 g N m^{-2} in summer maize.

Content and variations after the rotation of soil TN, SOC, and C:N ratios are described in Table S3. To compile with vermicompost treatments, N content was significantly higher than that in other treatments ($P < 0.05$), as shown in Table 1. In general, the amounts of nutrients in soil after the wheat and maize seasons are significantly higher than those after synthetic inorganic fertilization (NPK). The highest N retention in soil was observed in vermicompost with cow manure (VCM, Table 3). In addition, carbon content in VCM was higher than that in other treatments. Soil nutrients during the wheat–maize crop rotation were determined, and the amounts in all treatments had a range of 156–240 kg N ha^{-1}. The VCM showed lower uptake rates than VCMNPK and VPMNPK, whereas NPK showed significantly higher uptake rates than the other treatments ($P < 0.05$).

4. Discussion

4.1. NH_3 volatilization

The purple soil area of Sichuan is the main crop-producing region in the Sichuan Basin. A large amount of NH_3 is volatilized from the grain fields due to the use of chemical fertilizers. In our study, in the wheat–maize rotation system, considerable N loss through NH_3 volatilization occurred during early basal fertilization. It supported the findings in the current study, that ammonia plays a significant role in N cycle volatilization and deposition. The results of NH_3 volatilization emphasized that the vermicomposting load of all VCM treatments was lower than that of conventional composting. The possible reason was the slow utilization of N in the stabilized organic fertilizer and subsequent low N gas emissions (Raza et al., 2020). The initially high NH_3 volatilization rate in N fertilization in this study in wheat–maize rotation may be attributed to high soil pH (8–9). On the one hand, soil alkaline conditions promoted the transformation of the substrate NH_4^+-N into the gas form of NH_3 (Sommer et al., 2004).

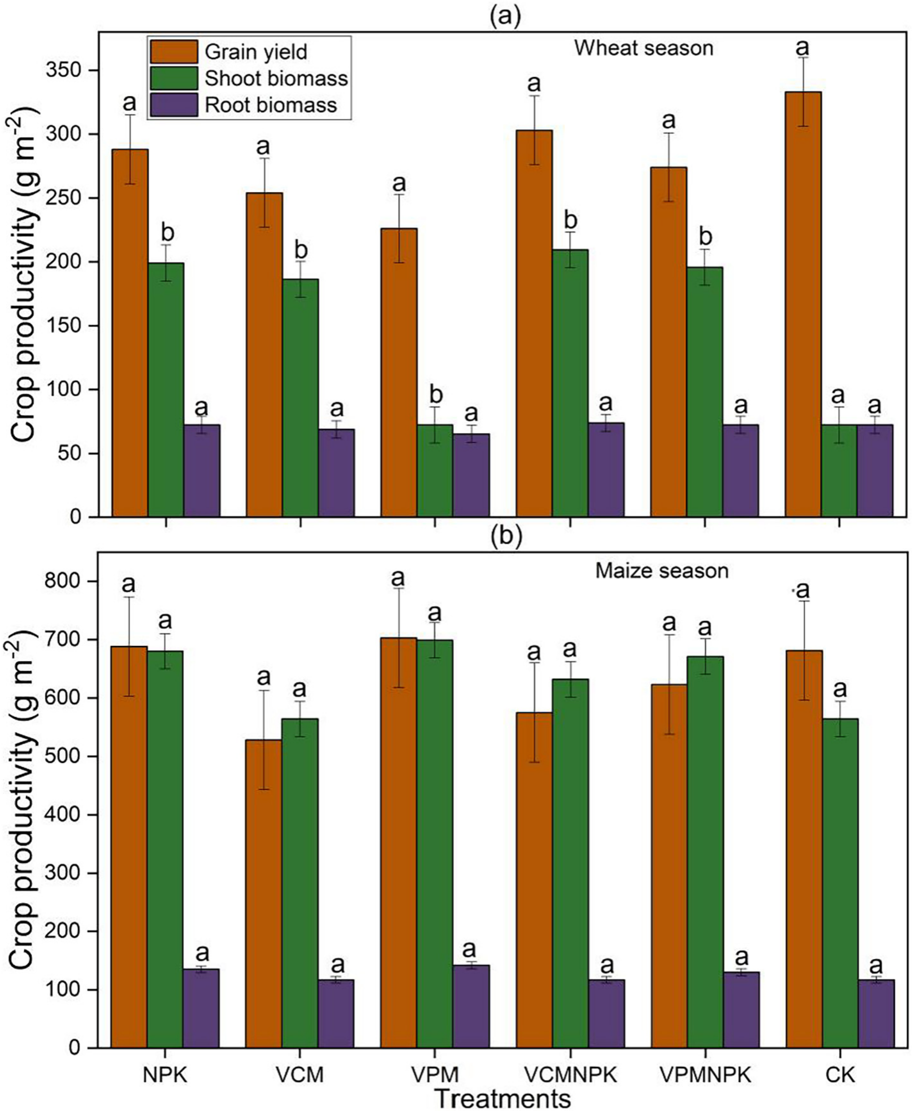

Fig. 5. Crop productivity during wheat (a), maize (b), seasons with vermicompost. Standard errors are represented by error bars (n = 3). Significant differences among treatments are indicated by different letters above the columns ($P < 0.05$).

The cumulative NH_3 flux from VPM was lower than that in other treatments, and similar results were reported by Huijsman et al. (2003). The specific nitrogen supply in agricultural soils can be hydrolyzed and converted into NH_4^+. NH_3 volatilization is crucial during the summer maize season in purplish soil (Zhang et al., 2015) and is an important factor for accurately measuring long-term flux in winter wheat at low temperatures and summer maize during high-frequency emissions. Substantial NH_3 loss is typically observed within 2 weeks after fertilization, contributing to overall seasonal loss (Cao et al., 2013; Mariano et al., 2019). In our study, the sustainable management of an agricultural system reduced NH_3 loss, particularly after the application of organic fertilizers (VCM and VPM). The differences in methods were the reason that the intensive and rapid application of N was able to promote NH_3 volatilization, as in previous studies of organic amendments (Zhou et al., 2016).

Table 1
Global warming potential (GWP) during wheat–maize rotation.

Treatments	Wheat season	Maize seasons
	GWP - CO_2/eq m^{-2}	
VCM	803.93a	540.61a
VPM	773.68a	576.28a
NPK	1032.4b	570.79a
VCMNPK	1143.15b	543.29a
VPMNPK	1010.19b	526.38a

Note: The different letters above the column indicate significant differences among treatments ($P < 0.05$).

4.2. N_2O, CH_4, and CO_2 emissions after vermicompost application

Carbon emissions generated by agricultural activities are important sources of greenhouse gas emissions, accounting for about 25 % of total emissions, and cropland is the largest N_2O emission source for terrestrial ecosystems due to the application of large amounts of chemical fertilizers. It needs to be applied in a specific amount because it is an essential factor in the stimulation of reactive N gas emissions (Dong et al., 2018). NH_3 volatilization and N_2O emission are influenced by soil microbial activity and substantial N dynamics in soil (Sun et al., 2013; Sun et al., 2021). According to previous studies at the study site, the soil temperature and soil water-filled porous surface with N_2O emissions might influence winter wheat and summer maize emissions in purplish soil (Zhou et al., 2018). N_2O losses may be attributed to low soil organic matter content (Ju et al., 2009). Another reason might be the high pH of purplish soil, which can lead to the denitrification of dinitrogen, as explained in previous studies (Butterbach-

Bahl et al., 2013). CH_4 emissions were monitored in the wheat and maize seasons. CH_4 in cropland acted as a small sink. Owing to its high oxidation rates in purplish soil, diffusion occurred within the subsoil during methanogenesis, as described in previous research at the same study site (Zhou et al., 2014a, 2015b, 2014c). CH_4 uptake and soil temperature were correlated during the wheat and maize seasons in a winter wheat season, and this correlation is the crucial mechanism in purplish soil. The correlations of CH_4 uptake with soil inorganic nitrogen (NH_4-N, NO_3-N), and change in DOC content in the soil are regulatory factors that can influence CH_4 fluxes during winter wheat and summer maize rotations in purplish soil. CH_4 uptake can be altered by different ecosystems and regional environmental conditions (Wang et al., 2014a, 2021b).

CO_2 emissions were influenced by environmental factors and fertilization during the wheat–maize rotation. In our study, organic amendments generated higher amounts of emissions than NPK and inorganic fertilization combined with vermicompost treatments, showing the same results as the treatments in previous studies (Ding et al., 2007). During the summer season, the emissions were lower in the early period but gradually increased and peaked at the start of August due to an increase in temperature. Our results can be attributed to increased SOC, in which mineralization increased CO_2 emissions (Al-Kaisi et al., 2008). Soil CO_2 emissions can be influenced by organic amendments and environmental factors,which is important to the maintenance of C balance during wheat–maize rotation in upland agricultural systems in purplish soil (Zhou et al., 2014a, 2015b, 2014c).

Vermicomposting was compared with inorganic amendment (Table 1), and GWP was determined in upland areas. A significant difference was observed between the treatments. The values were 773.6 and 803.9 g CO_2-eq m^{-2} in VCM and VPM during the wheat season, and 540.6 and 576.2 during the maize season compared with NPK (1032.4 and 570.7 g CO_2-eq m^{-2}) in respective seasons. The vermicompost (separately) treatments (VCM and VPM) showed lower GWP than the control (NPK). To the best of our knowledge, our research will be helpful to filling the gap in sustainable integrated agricultural systems. The simultaneous measurements of NH_3 volatilization, GHG emissions, and nutrient losses through leaching and recovery in crops and soil were documented.

4.3. Crop responses and N balance in wheat–maize rotation

The positive effects of vermicompost soil amendments may be due to the presence of available nutrients, large amounts of microbial life and diversity, and plant-growth-regulating hormones (Allardice, 2015), and thus, it is a potential source of nutrients for sustainable crop production (Suthar, 2009). The amounts of aboveground biomass and nutrients in the first established maize season were low but showed potential for growth and nutrient cycling (Doan et al., 2013a, 2013b).

The grain yield in the wheat–maize rotation system was non-significant ($P < 0.05$) in all the treatments. Crop productivity after vermicomposting alone showed no change. Crop growth and nutrient gain increased after vermicompost treatments but showed a nonsignificant change within treatments. Similar results were found in shoot biomass, and a non-significant change in biomass was observed in the early maize season (Doan et al., 2013a, 2013b). Unfertilized soil or soil subjected to a control treatment has a lower yield than fertilized soil because the soil fertility has been exhausted during the previous year. The short duration of the maize season with rapid growth in hot and humid climatic conditions obtained easily available sources of nutrients in NPK as compared with other organic treatments (Sharma and Banik, 2014), and the higher productivity of combined vermicompost treatments as compared to NPK in the wheat and maize seasons might be attributed to the low nutrient loss through leaching (Zhou et al., 2015b, 2015a; Singh et al., 2017). Moisture and temperature affect crop productivity. Hesham and Ahmed (2020) showed that soil amendments, such as vermicomposting, increased the productivity of wheat and maize by 4.0 % at two irrigation levels and indicated that irrigation at 75 % moisture depletion (irrigation deficit) decreased plant height, 100-grain weight, grain and straw yields, water applied to wheat (−16.8 %) and maize (−20 %) compared to that with higher irrigation level (50 % depletion).

Nitrogen balance (input–output) was based on the inputs and outputs of the fertilization treatment. Organic fertilizers, such as vermicompost, are recommended for N balance in upland ecosystems with purplish soil. TN as a fertilizer, N uptake, gas emissions, including NH_3 volatilization and N_2O, and NO_3 leaching were calculated as N balance for organic fertilizers compared with synthetic inorganic fertilizers (NPK). The reduction in the amounts of gases during vermicompost preparation and application in soil resulted in decrease in environmental loadings. Considerable N loss was observed during the maize season in summer due to the high infiltration capacity of purplish soil (Zhu et al., 2009). N loss through different pathways differed between the two seasonal crops.

The N balance for all treatments was calculated. VCM and VPM showed significantly higher levels than the other treatments ($P < 0.05$). In both seasons, the total input N was 280 kg N ha^{-1} for NPK and 260 kg N ha^{-1} for other vermicompost treatments, which were used with long-term fertilization in the study area. The N balance during the wheat–maize rotation is shown in Table 2.

On the basis of the simultaneous measurements of nitrogen loss through leaching and gaseous emissions with crop N uptake, we evaluated the N balances of vermicompost application (alone and combined with NPK) compared with conventional inorganic fertilizers in a wheat–maize crop rotation system. The N balance was calculated according to the inputs and outputs during wheat–maize rotation. NPK showed a value of 30.01 kg N ha^{-1}, and similar results were reported by Zhou et al. (2016). The possible reason was atmospheric N deposition for newly established study under vermicompost application. The organic amendment results showed good measures for N retention in purplish soil. The climatic conditions with maximum and minimum temperatures with rainfall during wheat–maize rotation are mentioned in the site description in Fig. 1. In present study showed that gaseous and hydrological N losses through leaching during the wheat–maize rotation system were detected more frequently in warm and wet seasons than in cooler and drier seasons. Our results were consistent with previous studies previously performed in this region. Specifically, gas emissions were higher in the maize seasons with warm and moist conditions than in the winter wheat season (Zhou et al., 2016; Zhu et al., 2009) after organic amendments, particularly vermicompost and NPK combined vermicompost. Compared with synthetic inorganic fertilizers, organic fertilizers can offer better results depending on numerous factors, including the type of soil and application rates.

Table 2

N balance during wheat–maize rotation during vermicompost application.

Treatments	Wheat-maize seasons (kg Nha^{-1})					N balance
	N fertilization	N uptake	N_2O flux	NH_3 flux	NO_3 leaching	
NPK	280	210.4 ± 20.8b	1.54 ± 0.0a	35.29 ± 4.3b	9.15 ± 2.3a	23.01a
VCM	260	155.7 ± 15.5a	1.65 ± 0.5ab	10.61 ± 0.53a	7.70 ± 2.7a	84.27b
VPM	260	173.0 ± 9.6ab	2.39 ± 0.2b	11.84 ± 1.82a	6.79 ± 2.2a	65.98b
VCMNPK	260	192.1 ± 18.5ab	1.17 ± 0.14a	23.21 ± 5.57ab	8.13 ± 0.6a	35.35ab
VPMNPK	260	197.38 ± 20.9ab	1.87 ± 0.15ab	22.20 ± 4.4ab	8.17 ± 2.4a	30.37ab

Note: The mean value of the three replicates after "±" signs show standard deviation ($n = 3$). The different letters above the column indicate significant differences among treatments ($P < 0.05$).

Table 3

Stepwise multiple regression between nutrients, crop productivity and gases emissions.

Explained variable	Regression equation	r^2	*P*
Wheat season NH_3 (Soil)	$Y = -1.536 + 0.086X_{wsb}-0.168X_{wrb} + 0.023X_{wg}$	0.566	<0.007
Maize season NH_3 (Soil)	Non-significant	–	–
Wheat season N_2O (Soil)	$Y = 0.0203 + 0.000X_{wsb}-0.001X_{wrb}-0.001X_{wg}$	0.566	<0.009
Maize season N_2O (Soil)	Non-significant	–	–
Wheat season CO_2 (Soil)	$Y = -34.921 + 01.839Xwsb-1.322X_{wrb}-0.041X_{wg}$	0.826	<0.000
Maize season CO_2(Soil)	Non-significant	–	–
Wheat season NH_3	$Y = 9.843 + 0.223Xwrn + 1.875Xwsn + 0.039Xwgn$ $+4.775Xwstn-22.155Xstn$	0.698	<0.031
Maize season NH_3	$Y = -14.359 + 0.806X_{mrn} + 4.193X_{msn}$ $+0.183Xmgn-20.460Xmstn + 13.354Xstn$	0.778	<0.009
SCN	$Y = 0.995–0.050X_{wNH3} + 0.853X_{wCH4}$ $+0.011X_{wCO2}–1.334X_{wN2O}-0.067X_{mNH3}–25.564Xm_{CH4} + 0.017X_{mCO2} + 17.880X_{mN2O}$	0.866	<0.035

Note: wsb represents wheat shoot biomass, wrb = root biomass, wg = grain, wrn = root nitrogen, wsn = shoot nitrogen, wgn = wheat grain nitrogen, wstn = wheat soil total nitrogen, stn = soil total nitrogen, and mrn = maize root nitrogen, msn = shoot nitrogen, mgn = grain nitrogen, mstn = soil total nitrogen, stn = soil total nitrogen. SCN = soil carbon nitrogen ratio.

4.4. Relationship between nutrients, crop productivity, and gas emissions

Stepwise multiple regressions showed the relationships among crop and soil nutrients, biomass production, and gas emissions (Table 3). NH_3 volatilization and N_2O and CO_2 emissions showed significant ($P < 0.05$) effects on shoot and biomass in addition to crop productivity in the wheat season but showed non-significant effects in the maize season. Thus, NH_3 volatilization showed significant effects on root N, shoot N, grain N, and soil total nitrogen in the wheat and maize seasons. In addition, overall soil total nitrogen showed significant effects. The results showed that NH_3 volatilization and GHGs emissions had significant ($P < 0.05$) effects on soil C:N ratios, as shown in Table 3. The C:N ratio is an important factor in agricultural systems and can increase or decrease gas emissions (Raza et al., 2021a, 2021b).

5. Conclusion

Vermicompost enhanced nutrient uptake in crops and improved nutrient status in the soil profile (18 % soil N in VCM). The increased content by uptake of nutrients and reduction in loss of nutrients influenced plant growth and soil fertility. The nutrients gained from the wheat–maize rotation through plant parts and purplish soil were found in excess for agricultural use as organic amendments. Wheat–maize rotation methods involving vermicompost practices and conservation of natural resources in the purplish soil of upland cropland are rarely reported.

In this study, we quantified the vermicomposting effects on ammonia volatilization, GHG emissions, and crop growth and production. The vermicompost treatments significantly reduced gas emissions during the wheat–maize rotation in an upland agro-ecosystem. The uptake of nutrients in the crops enhanced plant growth and the nutrients returned from vermicompost increased soil fertility. Vermicomposting is one of the most suitable eco-friendly technologies used in upland of purplish soil. This study proposed that nutrients from organic waste can be recycled and maintained in upland agro-ecosystem. N content in crops is significantly lower in organic treatments, and P, K contents in VCM and VPM content is higher than that in synthetic fertilizers. The regular pattern of fertilization in our field site, N deposition, and loss supported balancing N in upland areas. The environmental driving factors were the main constraints for the N budgets. The study also shows important evidences for performance of organic agriculture rather than solely using inorganic fertilizers.

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CRediT authorship contribution statement

Syed Turab Raza: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Bo Zhu:** Supervision, Funding acquisition, Project administration, Writing - review & editing. **Zhiyuan Yao:** Writing – review & editing. **Jianping Wu:** Supervision, Writing – review & editing. **Zhe Chen:** Writing – review & editing. **Zulfiqar Ali:** Writing – review & editing. **Jia Liang Tang:** Writing – review & editing.

Data availability

Data will be made available on request.

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.

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Appendix A. Supplementary data

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