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Short Communication

Substituting organic manure for compound fertilizer increases yield and decreases NH_3 and N_2O emissions in an intensive vegetable production systems

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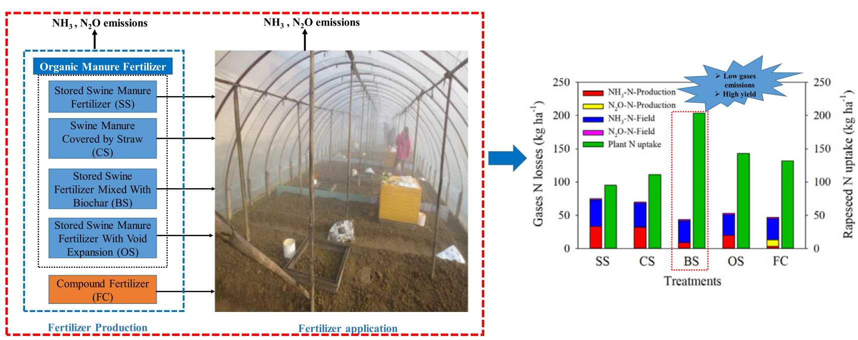
HIGHLIGHTS

- Gaseous N losses and yield varied with different fertilizer management practices.
- Organic manure substitution decreased gaseous N losses and increased yield.
- Reducing NH_3 under organic manure substitution should be considered.

GRAPHICAL ABSTRACT



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ABSTRACT

Substituting organic manure for compound fertilizer may play an important role in regulating the nitrogen (N) cycle and consequently affecting crop yield in agroecosystems. However, how substituting different organic manures for compound fertilizer affects crop yield and ammonia (NH_3) and nitrous oxide (N_2O) emissions in the vegetable system during the life-cycle production (including storage and field application) remains poorly elucidated. Thus, we conducted a greenhouse experiment to investigate the effects of substituting organic manure species, i.e., stored swine manure fertilizer (SS), swine manure covered by straw (CS), stored swine fertilizer mixed with biochar (BS), and stored swine manure fertilizer with void expansion (OS) for compound fertilizer (FC) on rapeseed yield and NH_3 and N_2O emissions in a rapeseed-cropping system in China. The results showed that the total gaseous N losses (NH_3 and N_2O) were 1.6, 1.4 and 1.1 times higher in SS, CS and OS than FC, respectively. However, total gaseous N losses in BS was 0.9 times less than FC. Compared with FC, rapeseed yield and N uptake in SS and CS were decreased by 17.2–20.2% and 16.0%–28.1%, respectively, but which were increased by 7.3% and 54.1% in BS, respectively. In addition, OS decreased rapeseed yield by 17.2%, but increased N uptake by 8.5%. Therefore, the effects of substituting organic manure for compound fertilizer on rapeseed yield, N uptake, NH_3 and N_2O varied regarding different organic manure species. Adopting stored swine fertilizer mixed with biochar might be a sound management practice to reduce gaseous N losses and enhance N uptake and yield in intensive vegetable production systems.

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1. Introduction

Synthetic nitrogen (N) fertilizer plays an important role in meeting the growing food demand for the increasing population in China over the past three decades (Gu et al., 2015; Li et al., 2013). However, an unreasonable use of N fertilizer in China has caused a series of environmental problems, including soil degradation, air and aquatic pollution (Ju et al., 2009). It is estimated >30% of applied N fertilizer is lost to the atmosphere via N losses, such as nitrous oxide (N_2O) emissions (Cui et al., 2018; Zhang et al., 2016) and ammonia (NH_3) volatilization (Bai et al., 2018; Gu et al., 2016), and also hydrological N losses (Fang et al., 2015; Diaz and Rosenberg, 2008; Ju et al., 2009).

To deal with the environmental issues caused by an unsustainable management of N fertilizer, the Chinese Ministry of Agriculture released the policy of "zero growth of fertilizer by 2020" plan in 2015. This governmental plan highlights the necessity of adopting improved N fertilizer management in croplands (Cui et al., 2013; Gu et al., 2017; Ju et al., 2009; Xia et al., 2017), such as adopting the substitution of organic manure for synthetic fertilizer (Xia et al., 2017). Currently, the proportion of livestock manure recycling to cropland in China on is only approximately 43% (Gu et al., 2015).

Increasing manure recycling could mitigate the adverse effects of manure storage on the environment (Bennetzen et al., 2016; Wang et al., 2017). A recent meta-analysis demonstrated that substituting organic manure for synthetic fertilizer could increase crop productivity by 6.8% (Xia et al., 2017). However, regarding gaseous N emissions, inconsistent results regarding the effects of manure substitution on NH_3 and N_2O emissions were observed in previous studies (Xia et al., 2017; Chadwick et al., 2011; Owen et al., 2015). This scenario could be largely attributed to the difference in manure management practices before field application (Neerackal et al., 2015; Holly et al., 2017). Various manure management practices (e.g., composting, anaerobic digestion and solid-liquid separation) lead to the difference in manure components and quality (e.g. C/N ratio), inevitably affecting NH_3 and N_2O emissions from downstream processes associated with field application (Duncan et al., 2017; Evans et al., 2018; Holly et al., 2017; Xia et al., 2017; Zhang et al., 2018). This highlights the importance of keeping track of emissions throughout manure management and its application to field (Holly et al., 2017; Owen et al., 2015; Zhong et al., 2013). However, comprehensive evaluation of the effects of substituting organic manure for N fertilizer on crop yield and gaseous N emissions throughout the manure life-cycle production and utilization has rarely been conducted. Moreover, previous studies only focused on staple food crops (i.e. wheat, rice and maize) rather than vegetables (Thelen et al., 2010; Xia et al., 2016; Xia et al., 2017; Zhong et al., 2013).

Vegetable production, accounting for 13.5% of the cultivated area of China in 2015 (Min and Shi, 2018; Huang et al., 2016), is characterized by a shorter growth period, 3–6 times higher synthetic N fertilizer inputs, and higher economic value compared with staple food crop production (Fan et al., 2018; Ju et al., 2009). This also produces much higher gases (e.g., N_2O and NH_3) emissions (Gong et al., 2013; Li et al., 2015; Liu et al., 2017), and consequently results in lower fertilizer use efficiency (Ju et al., 2009). Studies that explored the effects of different organic manure species on vegetable yield and gaseous N emissions are scarce (Liu et al., 2015; Xia et al., 2017). Therefore, we conducted a field experiment to investigate the effect of substituting organic manure for compound fertilizer on yield, as well as N_2O and NH_3 emissions in an intensive vegetable production system in China. Our hypotheses were: 1) Substituting organic manure for compound fertilizer increases vegetable yield and reduces N_2O and NH_3 emissions; 2) the intensities of such effects are affected by the organic manure species.

2. Materials and methods

2.1. Experiment sites

The experiment was conducted in a typical greenhouse in a rapeseed cropping system in Daxing district, Beijing, China (39°26′N, 116°13′E) (Fig. 1). During this period, the mean temperature inside greenhouse is 26.8 °C, with the lowest temperature of 24.8 °C and the highest of 30.2 °C. The topsoil (0–20 cm depth) in the greenhouse has a pH of 7.3, and contains 28.2 g kg^{-1} organic matter, 0.55 mg kg^{-1} NH_4-N, 93.47 mg kg^{-1} NO_3-N, and 2.5 g kg^{-1} total N.

2.2. Experimental design

The experiment divided into fertilizer production and application stages. Fertilizer production included four organic manure types and one compound fertilizer type. Fresh swine manure and corn straw were the raw materials of organic manure production, and their detailed chemical characteristics were shown in Table 1. Based on the field investigation and expert interview of Chinese Academy of Agricultural Sciences, we designed four organic manure types during production stage (Table 2), viz. stored swine manure fertilizer (SS), swine manure covered by straw (CS), stored swine fertilizer mixed with biochar (BS), stored swine manure fertilizer with void expansion (OS). In addition, we purchased the compound fertilizer (FC) from local market, and its ratio of nitrogen (N):phosphorus (P):potassium (K) was 16%:16%:16%.

Rapeseed (*Brassica chinensis* L.) was sown on 10 July 2017 and harvested on 11 August 2017 while the agricultural managements followed. The experiment included 5 treatments (SS, CS, BS, OS and FC) with 3 replicates totaling 15 experimental plots. According to local fertilization practice, we applied the basal fertilizer once at 200 kg N ha^{-1} at each treatment after sowing the rapeseed seeds.

2.3. Greenhouse gases measures

The NH_3 and N_2O emissions in this study include organic manure production and application that cover 50 and 33 days, respectively. The emissions of NH_3 and N_2O were measured using the Dräger-Tube method described by Ni et al. (2014) and static-chamber-gas chromatography as used by Zhuang et al. (2019), respectively. The chambers with a size of 50 cm wide × 50 cm long × 50 cm tall were used for gas sampling. The gas fluxes were collected between 09:00 am and 11:00 am during the total experimental periods. Gas sampling in organic manure production was conducted daily for the first week after stacking, then once every two days 8–14 days after stacking, once every three days during 15–21 days after stacking, once every five days during 22–28 days after stacking, and once every week during 29–50 days after stacking until application. Gas sampling in compound fertilizer and manure application was conducted daily for the first five days after sowing, then once every two days 6–11 days after sowing, once every three days during 12–20 days after sowing, and once every four days during 21–33 days after sowing until harvest. NH_3 and N_2O samples were analyzed by NH_3 concentration detection tube (Drägerwerk AG, Lübeck, Germany) and a gas chromatograph (Agilent 7890A, USA), respectively. In addition, we adopted the emission factors to calculate NH_3 and N_2O emissions during the compound fertilizer production stage (Sun and Wang, 1997; Xia et al., 2016). Finally, we evaluated total NH_3 and N_2O emissions during the fertilizer production and application stages.

2.4. Biomass and nitrogen measurement

At harvest time on 11 August 2017, we randomly selected three quadrats for each treatment, and collected the samples of rapeseed. The rapeseed samples were measured for fresh weight. In addition, at

Fig. 1. Location of experiment site in Daxing district, Beijing, China. Map.

harvest, the rapeseed samples were oven dried at 105 °C for 15 min, and then at 75 °C until constant weight for N measurements. We adopted the Kjeldahl molybdovanadate method to measure the N concentrations (Page, 1982).

2.5. Statistical analysis

The effects of substituting different organic manures for compound fertilizer on the NH_3 volatilization, N_2O emission, yield, total gases-N losses and plant N uptake were evaluated using one-way analyses of variance (ANOVA). Least significance difference (LSD) was used to compare the significant differences of means for all parameters among all treatments at the 0.05 level. $p < 0.05$ denotes the significant difference among treatments, and vice versa. All these analyses were performed using SPSS ver. 19.0 statistical software (SPSS Inc., Chicago, IL, USA).

Table 1
Characteristics of the raw materials (mean ± s.e., the number of replicates (N) = 3.)

Raw material	Total carbon (g kg^{-1}DM)	Total nitrogen (g kg^{-1}DM)	Water content (%)	Carbon: nitrogen
Swine manure	387.8 ± 7.9	25.2 ± 1.1	38.1 ± 1.2	15.5 ± 0.7
Corn straw	413.2 ± 22.5	10.1 ± 0.6	11.1 ± 1.5	41.3 ± 0.7
Biochar	527.0 ± 15.5	7.8 ± 1.3	32.5 ± 2.1	67.6 ± 11.4

Note: DM: dry matter.

3. Results and discussions

3.1. The NH_3 volatilization and N_2O emission under fertilizer production

NH_3 volatilization in four manure treatments rapidly reached their peaks after three days since the commencement of the manure storage (Fig. 2), consistent with previous results (Wang et al., 2014; Yuan et al., 2014). This phenomenon can be explained by the rising temperature and NH_4-N at the beginning of fermentation of the mixed swine manure and straw (Pagans et al., 2006; Yuan et al., 2014). Three days later, NH_3 volatilization from the four treatments showed a decreasing trend with some fluctuation, and finally dropped to a negligible level 50 days (Fig. 2). The cumulative NH_3 volatilization from SS, CS, BS and OS were 567.7, 341.8, 284.5 and 318.7 g N m^{-2}, respectively (Fig. 2). Compared with SS, NH_3 volatilization was significantly decreased for CS, BS and OS ($p < 0.05$). This result indicated that increased manure void expansion or added biochar could reduce NH_3 volatilization. It has been reported that straw increased the amount of degradable carbon, which could promote the immobilization of ammonium into microbial biomass (Wang et al., 2012; Wang et al., 2017), increase the C/N ratio and improve aeration conditions in the manure (Wang et al., 2014).

Table 2
Characteristics of different manure (mean ± s.e., the number of replicates (N) = 3.)

Treatments	Total carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Water content (%)	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})	pH
SS	25.9 ± 1.4	2.1 ± 0.2	25.1 ± 0.8	0.5 ± 0.1	75.4 ± 8.8	7.7 ± 0.4
CS	26.1 ± 0.4	2.2 ± 0.2	24.8 ± 0.9	0.5 ± 0.1	66.3 ± 4.2	7.9 ± 0.2
BS	32.2 ± 3.3	2.9 ± 0.4	26.1 ± 1.2	0.5 ± 0.1	72.1 ± 5.2	7.4 ± 0.2
OS	28.8 ± 2.9	2.5 ± 0.3	24.5 ± 1.6	0.6 ± 0.1	66.5 ± 3.6	7.5 ± 0.4

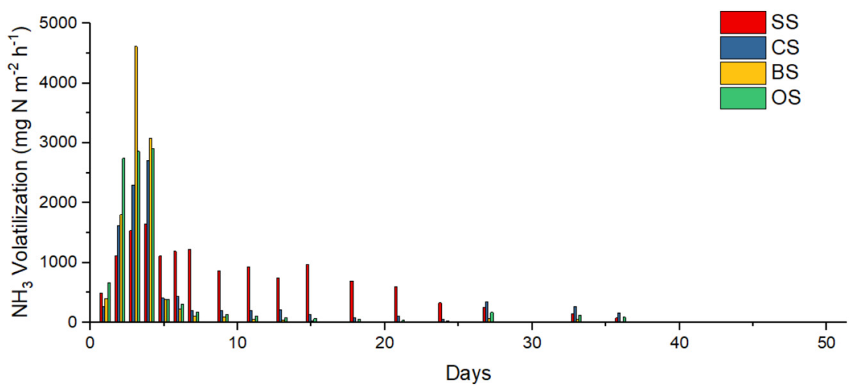

Fig. 2. The characteristics of NH_3 volatilization under different manure treatments.

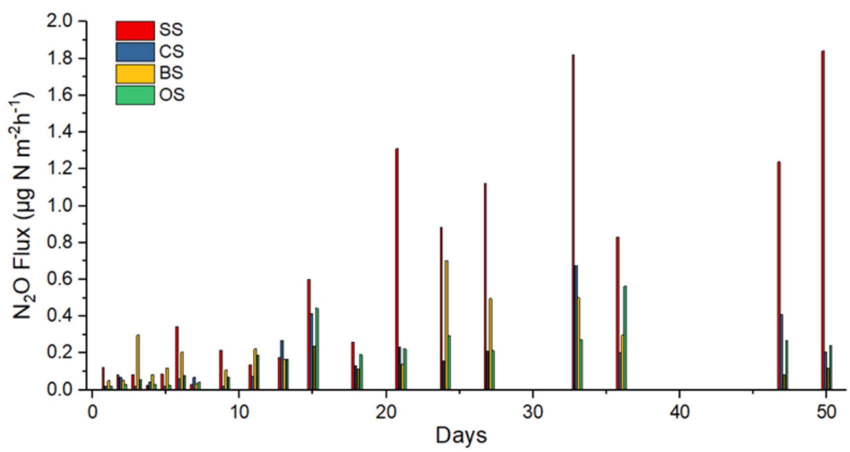

Fig. 3. The characteristics of N_2O emission under different manure treatments.

Unlike NH_3 volatilization, N_2O emission in four manure treatments mainly occurred in the mid and later period of manure storage (Fig. 3), which was also observed in previous studies (Jeong et al., 2018). With the extension of manure treatment, the NH_4-N in manure decreased, but NO_3-N and NO_2-N increased (Yuan et al., 2014; Jiang et al., 2011, 2013; Wang et al., 2017), and thus stimulated the N_2O emission (Chadwick et al., 2011; Monteny et al., 2006). The cumulative N_2O emission from SS, CS, BS and OS were 1.0, 0.3, 0.3 and 0.3 g N m^{-2}, respectively (Fig. 3). CS, BS and OS significantly decreased the NO_2 emission when compared with SS ($p < 0.05$). These results demonstrated that manure void expansion or added biochar could be an effective way to reduce N_2O emission, which was consistent with previous studies (Chadwick, 2005).

3.2. NH_3 volatilization and N_2O emission after fertilizer application

NH_3 volatilization in all treatments reached their peaks after four days of fertilizer application, and then decreased with fluctuations (Fig. 4). Compared with CF, SS significantly increased the cumulative NH_3 volatilization ($p < 0.05$). Cumulative NH_3 volatilization in FC (3.1 g m^{-2}) was 2.8% and 11.8% lower than in CS (3.6 g m^{-2}) and BS (3.2 g m^{-2}), respectively, but 1.6% higher than that in OS (3.1 g m^{-2}). There were no significance of NH_3 volatilization among FC, CS, BS and OS treatments ($p > 0.05$). These results were inconsistent with the meta-analysis results of Xia et al. (2017), who found that substituting a different organic manure for compound fertilizer decreased NH_3 volatilization by 23%. This could be attributed to the soil NH_4-N content in different organic manure species applications, microbial activity levels (Sun et al., 2014; Zhou et al., 2016; Evans et al., 2018) and the ratio of manure substitution (Xia et al., 2017).

N_2O emission in all treatments increased rapidly and reached their peaks one day after fertilizer application and irrigation, and then showed a decreasing trend (Fig. 5). Cumulative N_2O emission in OS and BS was significantly lower than those in FC ($p < 0.05$), which was

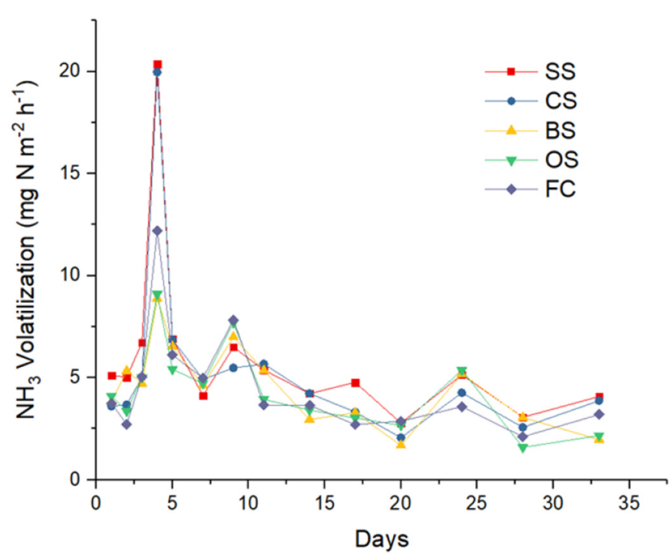

Fig. 4. The characteristics of NH_3 volatilization after different fertilizers application.

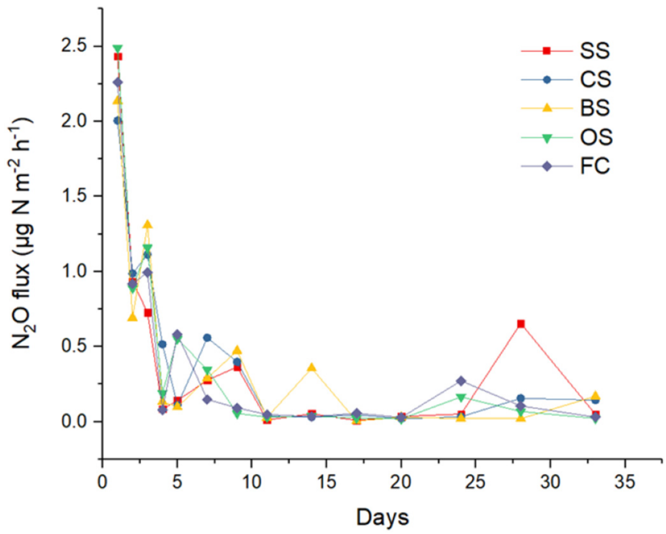

Fig. 5. The characteristics of N_2O emission after different fertilizers application.

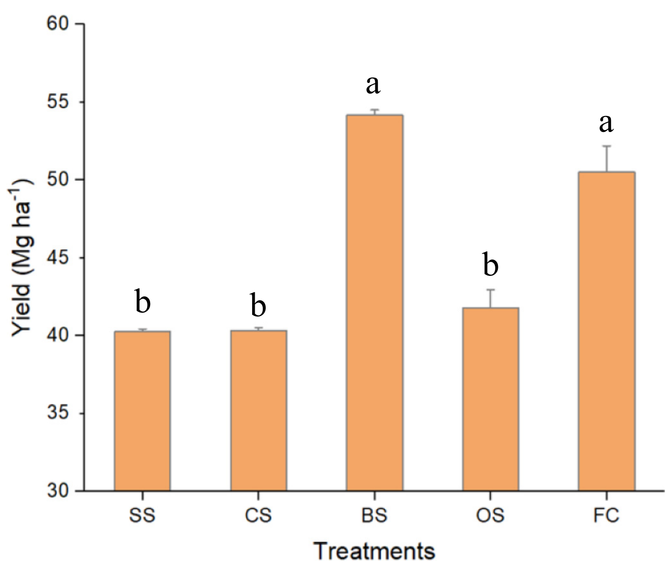

Fig. 6. The rapeseed yield under different fertilizer treatments.

consistent with previous studies (Liu et al., 2015; Xia et al., 2017; Ozlu and Kumar, 2018). This could be attributed to the increase in inorganic N immobilization through microbial activity after organic manure application, reduced substrate availability for nitrification and denitrification (Wang et al., 2015; Zhou et al., 2016), and promoted the plants' inorganic N uptake (Xia et al., 2017). In contrast, cumulative N_2O emission in SS were slightly higher than that in FC ($p > 0.05$), which is inconsistent with the results of Xia et al.'s (2017) meta-analysis. We attributed the higher N_2O emissions in SS treatment to increased NH_4-N in soil, likely increased N_2O emission (Holly et al., 2017).

3.3. Rapeseed yield

Compared with FC, SS, CS and OS significantly decreased the rapeseed yield (Fig. 6) ($p < 0.05$). The decrease in yield in SS, CS and OS demonstrated that manure substitution generally cannot provide enough available N for vegetable growth due to the slow mineralization than ready-to-use chemical N fertilizer (Pincus et al., 2016; Xia et al., 2017). However, BS in comparison with FC slightly increased the rapeseed yield ($p > 0.05$). Various yield results following substitution of different organic manures species for compound fertilizer may depend on the balance between the release rate of mineral N during decomposition of the organic manure and the N demand of rapeseed (Chivenge et al., 2011; Chen et al., 2014; Xia et al., 2017), and likely the level of the soil inorganic N sequestration through microbial activity (Chivenge et al., 2011).

3.4. Gaseous N losses and plant N uptake under different N fertilizer management

We comprehensively estimated gaseous N emissions under N fertilizer production (200 kg N) and application (200 kg N ha^{-1}). Results showed that total gaseous N losses for FC (46.8 kg N) during the fertilizer's production and application was significantly lower than that for SS (75.0 kg N), CS (69.6 kg N) ($p < 0.05$), and had no significance for OS (52.7 kg N) and BS (43.2 kg N) (Table 3) ($p > 0.05$). However, plant N uptake following different organic manure species applications showed an opposite trend from FC (Table 3). Among all organic manure species, BS significantly increased the plant N uptake when compared to CK (Table 3) ($p < 0.05$). This indicated that the impacts on gaseous N losses and plant N uptake of substituting organic manure for compound fertilizer were dependent on the organic manure species. Substituting stored swine fertilizer mixed with biochar for compound fertilizer decreased gaseous N losses by 7.6% and increased plant N uptake by 54.1%, replicating previous research showing that substituting organic manure for compound fertilizer significantly increased plant uptake and then decreased further gaseous N losses (Chivenge et al., 2011; Wang et al., 2015; Xia et al., 2017).

4. Conclusion

We comprehensively estimated the effects of substituting different organic manure species for compound fertilizer on yield, NH_3 and N_2O emissions in a rapeseed-cropping system. We found that these effects were dependent on the organic manure species. Substituting stored swine fertilizer mixed with biochar effectively reduced gaseous N losses and increased rapeseed yield and N uptake and seems to be a promising management practice in comparison with other organic manure species. However, we also note that NH_3 volatilization from manure storage and application in stored swine fertilizer mixed with biochar were 19.9% higher than those from compound fertilizer.

Table 3
The fate of N under different fertilizer treatments (mean ± s.e., the number of replicates (N) = 3.)

Treatments	NH_3-N-production (kg)	N_2O-N-production (kg)	NH_3-N-Field (kg ha^{-1})	N_2O-N-field (kg ha^{-1})	Total gases-N losses (kg)	Plant N uptake (kg ha^{-1})
SS	32.91 ± 2.18a	0.06 ± 0.00b	39.8 ± 5.94a	2.2 ± 0.07a	74.97 ± 6.36a	94.96 ± 7.64c
CS	32.09 ± 3.96a	0.03 ± 0.00c	35.5 ± 4.58ab	2 ± 0.03ab	69.62 ± 5.83a	110.95 ± 7.76b
BS	9.14 ± 0.93c	0.01 ± 0.00c	32.2 ± 1.48b	1.9 ± 0.01b	43.24 ± 1.86b	203.53 ± 15.6a
OS	19.96 ± 1.21b	0.02 ± 0.00c	30.8 ± 3.72b	1.9 ± 0.03b	52.68 ± 4.23b	143.31 ± 11.7b
FC	3.19 ± 0.00d	10.2 ± 0.00a	31.3 ± 3.65b	2.1 ± 0.05a	46.79 ± 3.83b	132.11 ± 16.4b

Note: Different letters indicate significant differences among treatments ($p < 0.05$).

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