

# Interactive effects of synthetic nitrogen fertilizer and composted manure on ammonia volatilization from soils

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**Abstract** When synthetic fertilizer is co-applied with composted manure (compost), the high urease activity of compost may stimulate urea hydrolysis, thus increasing  $\text{NH}_3$  volatilization when urea is co-applied as a synthetic fertilizer. In this study, the interactive effects of compost type (low vs. high urease activity, referred to as CL and CH, respectively) and synthetic fertilizer form (urea vs. ammonium sulfate) were assessed in a 60-day greenhouse study. The compost was applied as a basal fertilization only at the initiation of the experiment, and the fertilizers ( $^{15}\text{N}$  labeled or not) were split into basal and additional fertilization. During the 10 days after the basal fertilization, co-application of CL with urea did

not increase  $\text{NH}_3$  volatilization as compared with urea alone treatment. However, co-application of CH with urea resulted in a significant increase in  $\text{NH}_3$  volatilization by more than 3-fold, not only from applied fertilizer- $^{15}\text{N}$  but also from compost and/or soil over the other two (urea alone and urea with CL) treatments. Meanwhile, when ammonium sulfate was co-applied with CH,  $\text{NH}_3$  volatilization from fertilizer became 3-fold lower than that when urea was co-applied. During the second 10 days after the application of urea as an additional fertilizer, the amount of  $\text{NH}_3$  volatilization from CH-treated soil did not differ from that observed with CL, and this is probably attributable to a reduction in urease activity in soils over time. These results indicate that not only the combination of compost and synthetic fertilizer, but also the time difference between the application of compost and synthetic fertilizer, are crucial to reducing  $\text{NH}_3$  volatilization.

**Keywords** Ammonium sulfate · Composted manure · Nitrogen loss · Urea · Urease activity

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## Introduction

The co-application of compost and supplementary synthetic N fertilizer is considered to be an alternative to conventional fertilization strategies, which depend solely on synthetic fertilizer or compost (Sikora and

Enkiri 2001; Parkpian et al. 2003; Schoenau and Davis 2006; Helgason et al. 2007). The advantages of the co-application technique as opposed to a single application include the curtailment of synthetic fertilizer consumption (Aggarwal et al. 1997; Nevens and Reheul 2003) and the amelioration of nutrient accumulation (especially P) in soils (Eghball and Power 1999; Eghball 2002).

Several studies have been conducted regarding the effect of compost application on the fate of co-applied N fertilizer in soil and plant systems. For example, the co-application of compost has been demonstrated to increase the plant uptake of fertilizer N via biotic and abiotic N retention that reduces N loss from soils (Choi et al. 2001). Land application of compost enriched with organic C stimulates the activities of heterotrophs that immobilize  $\text{NH}_4^+$ , contributing to a biotic N retention (Hadas et al. 1996; Siva et al. 1999; Han et al. 2004). An abiotic N retention is largely achieved via  $\text{NH}_4^+$  binding on to the negatively charged sites of compost humic substances (Siva et al. 1999; Butler et al., 2001; Devêvre and Horwath 2001; Castells et al. 2004). This can be considered to represent a positive interaction of the co-application of compost and urea with regard to N retention.

Although compost may increase the total recovery of co-applied fertilizer N in a soil-plant system, the co-application of compost may enhance the  $\text{NH}_3$  volatilization of fertilizer N, particularly in case of ammonia-based fertilizer, as the consequence of the high pH of compost at values in excess of 8.0 (Larney and Olson 2006; Kim et al. 2008). As manure, which is one source material of compost, harbors ureolytic microorganisms, the volatilization of  $\text{NH}_3$  may be most significant when urea and manure-based compost are co-applied (Varel 1997; Rochette et al. 2009). Urea is one (40% of total synthetic fertilizer consumption) of the most extensively utilized synthetic fertilizers (International Fertilizer Industry Association 2006), and is rapidly hydrolyzed by urease to  $\text{NH}_3$  within 1 week in soil (Han et al. 2004). The protonation of  $\text{NH}_3$  via  $\text{NH}_3 + \text{H}_2\text{O} \rightarrow \text{NH}_4^+ + \text{OH}^-$  after urea hydrolysis is the most critical process in the increase of soil pH to values in excess of 8, thereby resulting in an increase in  $\text{NH}_3$  volatilization (Fenn and Hossner 1985). This hypothesis has been previously evaluated by Choi et al. (2007) in a 10-day laboratory incubation study. In this study, the researchers detected a linear relationship between the

co-application rate of compost and a series of biological and chemical indices associated with  $\text{NH}_3$  volatilization including urea hydrolysis rate and soil pH elevation. However, until now, such effects of compost with high urease activity on the  $\text{NH}_3$  volatilization of co-applied urea have never been investigated with soils under cultivation.

Considering the potential interaction between compost and urea, it may be hypothesized that the use of composts with relatively low urease activity and synthetic fertilizers such as ammonium sulfate, which is less susceptible to  $\text{NH}_3$  volatilization as compared to urea (due to its acidic properties), would result in a diminution of  $\text{NH}_3$  volatilization. The application of compost and N fertilizer separately, i.e. compost as a basal fertilizer followed by the application of synthetic fertilizer as an additional fertilizer, may also prove an effective alternative to the conventional fertilization protocol (the application of compost and fertilizer N simultaneously as basal fertilizer followed by fertilizer N alone as an additional fertilizer) by avoiding direct contact between the compost and fertilizer. The objectives of this study were to assess the interactive effects of compost type (low vs. high urease activity) and synthetic fertilizer form (urea vs. ammonium sulfate) on  $\text{NH}_3$  volatilization when they are co-applied at the initiation (basal fertilization) or in the middle (additional fertilization) of cultivation. Such information may be useful in the development of better co-application strategies for the reduction of  $\text{NH}_3$  volatilization.

## Materials and methods

### Soil, composts, and synthetic fertilizers used

This study was conducted in a greenhouse in an experimental farm (126°36'08"E, 35°10'21"N) with Chinese cabbage (*Brassica campestris* L. cv. Sambok) at the Chonnam National University in Gwangju, Republic of Korea. The texture of the soil was sandy loam, classified in the Soil Taxonomy as coarse loamy Fluventic Haplaquepts (Rural Development Administration 2000). In order to select livestock manure-derived composts with contrasting urease activities but with similar other properties, 12 commercially available composts were purchased from markets and analyzed

for urease activities, as well as some chemical properties. The urease activities (expressed as the amount of urea hydrolyzed per unit weight of compost) of the 12 composts ranged between 257 and 8914  $\mu\text{g g}^{-1}$ . Two composts, showing contrastingly low (referred to as CL) and high (CH) urease activities, whilst displaying similar values for other chemical properties, were selected for the experiment (Table 1). Both compost appeared as stable (or mature) in terms of composting because C/N ratio was low (11.9 and 11.5 for CL and CH, respectively) and concentration of  $\text{NO}_3^-$  (3,502 mg and 2,464 mg N  $\text{kg}^{-1}$ , respectively) was considerably higher than that of  $\text{NH}_4^+$  (221 and 329 mg N  $\text{kg}^{-1}$ ) (Table 1) (Diaz and Savage, 2007). However, CH seemed less stable as compared with CL as indicated by the lower ratio of  $\text{NO}_3^-$ -N to  $\text{NH}_4^+$ -N in CH (7.5) than that in CL (15.8) (Table 1). This might be one reason of the relatively higher urease activity in CH than CL.

Urea (U) and ammonium sulfate (AS) were employed as synthetic fertilizers (SF). In order to discriminate the  $\text{NH}_3$  volatilization of applied SF from that of soil or applied compost,  $^{15}\text{N}$ -labeled (5.0  $^{15}\text{N}$  atom %) urea and ammonium sulfate were employed when necessary (see below).

#### Treatments and experimental layout

Nine treatments were laid out in a  $3 \times 3$  factorial experiment using three compost (none, C0; low urease, CL; high urease, CH) and three SF (none,

F0; urea, FU; ammonium sulfate, FAS) treatments (Table 2). Compost was applied at 15  $\text{ton ha}^{-1}$  (5.4  $\text{ton ha}^{-1}$  as dry basis) as basal fertilization with or without SF. Synthetic fertilizer was split into basal and additional fertilization (110  $\text{kg N ha}^{-1}$  as basal and 300  $\text{kg N ha}^{-1}$  as additional fertilization) in accordance with the recommendations of the Korean government for the cultivation of Chinese cabbage. As SF was applied twice, the  $^{15}\text{N}$ -unlabeled and labeled SF was alternately applied to determine the  $\text{NH}_3$  volatilization from basal and additional fertilizer separately. For example,  $^{15}\text{N}$ -unlabeled SF was applied as the basal fertilizer, followed by the application of  $^{15}\text{N}$ -labeled SF as an additional fertilizer in order to assess  $\text{NH}_3$  volatilization from the additionally applied SF.

Three blocks (8 m  $\times$  3 m each) were prepared for an experiment in a completely randomized block design with three replicates. A total of 15 single-vegetable trenches (30 cm in depth and 25 cm in diameter for each trench) was prepared in each block: three for treatments without SF (treatment code: C0-F0, CL-F0, and CH-F0), four for SF without compost (C0-FU and C0-FAS), and eight for SF with compost (CL-FU, CL-FAS, CH-FU, and CH-FAS). For SF treatment,  $^{15}\text{N}$ -labeled and unlabeled SFs were alternately applied as basal and additional fertilizers or vice versa, resulting in two trenches for each treatment. Plastic film was inserted into the trench in order to prevent lateral movement of water and nutrients, after which

**Table 1** Selected properties of the soil and compost; values are the means with standard error of the means in parentheses (n=4)

Properties <sup>a</sup>	Soil	Compost with low urease activity (CL)	Compost with high urease activity (CH)
pH <sub>water</sub>	6.3 (0.1)	8.0 (0.1)	8.1 (0.1)
Urease activity ( $\mu\text{g g}^{-1}$ )	196 (20)	257 (23)	8625 (357)
Total organic C ( $\text{g kg}^{-1}$ )	14 (1)	253 (53)	266 (37)
Total N ( $\text{g kg}^{-1}$ )	1.4 (0.03)	21.2 (1.4)	23.1 (2.1)
$\text{NH}_4^+$ -N ( $\text{mg kg}^{-1}$ )	3.2 (0.1)	221 (48)	329 (74)
$\text{NO}_3^-$ -N ( $\text{mg kg}^{-1}$ )	5.3 (0.2)	3,502 (252)	2,464 (325)
C/N ratio	10.1 (0.1)	11.9 (0.6)	11.5 (0.3)
Total P ( $\text{g kg}^{-1}$ )	0.4 (0.01)	24.7 (0.5)	29.8 (1.3)
Cation exchange capacity ( $\text{cmolc kg}^{-1}$ )	10.2 (0.3)	72.4 (3.7)	69.2 (5.7)

<sup>a</sup> pH was measured at a w/w ratio of 1:5 and 1:10 (sample:H<sub>2</sub>O) for soils and composts, respectively; urease activity (expressed as the amount of urea hydrolyzed per unit weight of sample) using the diacetyl monoxime method (Tabatabai, 1994); total C and N concentrations with a combustion method (Nelson and Sommers, 1996);  $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentrations using the steam distillation method (Mulvaney, 1996); total P concentrations, using the vanadomolybdo-phosphoric acid colorimetric method (Kuo, 1996); cation exchange capacity with 1-N ammonium acetate method (Sumner and Miller, 1996).

**Table 2** Experimental settings used

Code <sup>a</sup>	Type of amendments	Application rate				
		Compost	Synthetic fertilizer (SF)	Basal		Additional
				Compost (g plot <sup>-1</sup> )	SF (g N plot <sup>-1</sup> )	
C0-F0	NA <sup>b</sup>	NA	0	0	0	
CL-F0	CL	NA	27	0	0	
CH-F0	CH	NA	27	0	0	
C0-FU	NA	Urea	0	0.55	1.484	
CL-FU	CL	Urea	27	0.55	1.484	
CH-FU	CH	Urea	27	0.55	1.484	
C0-FAS	NA	AS	0	0.55	1.484	
CL-FAS	CL	AS	27	0.55	1.484	
CH-FAS	CH	AS	27	0.55	1.484	

<sup>a</sup>C0, CL, and CH indicate no compost application, compost with low urease activity, and compost with high urease activity, respectively; and F0, FU, and FAS denote no fertilizer, urea, and ammonium sulfate application, respectively. <sup>b</sup>NA, not applied. <sup>c</sup>Compost application rate is on dry matter basis and equivalent to 5.4 ton ha<sup>-1</sup> and synthetic fertilizer rate is equivalent to 110 kg N ha<sup>-1</sup> and 300 kg N ha<sup>-1</sup> for basal and additional, respectively

the trenches were refilled and used for experimental plots. The top 5 cm of soil was removed and mixed with compost (if necessary as in Table 2), P (as CaHPO<sub>4</sub> at 110 g P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>) and K (as KCl 15.6 g K<sub>2</sub>O ha<sup>-1</sup>), and the mixtures were placed back to the experimental plots. Ten days after the application of compost, one seedling of Chinese cabbage (*Brassica campestris* L. cv. Sambok) was planted per plot, and SF was applied evenly as a solution (1,000 mg NL<sup>-1</sup>) onto the surface of each plot using a pipette. Twenty-four hours after the application of SF (after allowing partial hydrolysis of urea), pH of the soils was determined with a pH meter (IQ150, Spectrum technologies, East-Plainfield, IL) at 1:5 (w/w) of soil:H<sub>2</sub>O ratio in order to investigate changes in soil pH as affected by compost and SF application. Ten grams of soil (on wet basis) were used for pH determination and placed back to the plots to conserve applied <sup>15</sup>N.

The additional SF fertilization was conducted 30 days after the basal fertilization, using the same procedure as for the basal fertilization. Immediately after each application of fertilizer, an NH<sub>3</sub> trap (a vial containing 10 mL of 0.005 mol L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub>) was positioned on the surface of each experimental plot and covered with a 250 mL glass bottle in order to collect volatilized NH<sub>3</sub> from the surface of the soil. After 10 days of NH<sub>3</sub> trap installation, the traps were

removed and analyzed for concentration and <sup>15</sup>N atom % of NH<sub>4</sub><sup>+</sup>. The duration of the NH<sub>3</sub> trap placement was determined on the basis of the study of Choi et al. (2007), who reported that the majority of NH<sub>3</sub> volatilization was completed within 7 days, using similar types of soils and fertilizers. Watering was conducted every other day in order to maintain a volumetric water content of 25% (checked using a time domain reflectometry and that is about 35 kPa of water potential) throughout the entire experiment.

#### Analytical procedures

The soil and compost samples were passed through a 2 mm sieve, and then used for analyses. All analyses were conducted using air-dried soil and freeze-dried compost samples except for urease activity, which was measured using moist samples. The dried samples were ground into fine powder using a ball mill (MM 200, Retsch GmbH, Haan, Germany) and then employed for total C and N analysis. The methods are described in detail in the footnote of Table 1.

The amount of volatilized NH<sub>3</sub> from the soils was determined via the titration of the trap (10 mL of 0.005 mol L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub> solution) containing NH<sub>4</sub><sup>+</sup> with 0.01 mol L<sup>-1</sup> NaOH to a pH of 5.4 with the aid of a pH meter. After titration, the solutions were adjusted

to pH 3 using  $0.05 \text{ mol L}^{-1} \text{ H}_2\text{SO}_4$  and evaporated to dryness at  $65^\circ\text{C}$  in an oven (Feast and Dennis 1996). The atom %  $^{15}\text{N}$  of the powder (ammonium sulfate) was analyzed with a continuous-flow stable isotope ratio mass spectrometer (IsoPrime EA, Micromass, UK) linked to a CN analyzer (NA Series 2, CE Instruments, Italy). Pure  $\text{N}_2$  (atom %  $^{15}\text{N}=0.3655 \pm 0.0001$ ) gas was employed as a reference.

#### Calculations and statistical analysis

The amount of  $\text{NH}_3$  volatilization in each plot was calculated based on the area covered with a bottle placed over a  $\text{NH}_3$  trap vial, after which the  $\text{NH}_3$  volatilization amount per ha was calculated. The amounts of volatilized N derived from  $^{15}\text{N}$ -labeled SF (NDFV) and that from compost and soil (NDFCS) were computed using the following equations (Hauck and Bremner 1976):

$$\text{NDFV} = T \times (A_S/A_F) \text{ and } \text{NDFCS} = T - \text{NDFV}$$

in which the T and  $A_S$  are the N content and atom%  $^{15}\text{N}$  excess (relative to the atmospheric  $\text{N}_2$  atom %  $^{15}\text{N}$  of 0.3663%) of volatilized total  $\text{NH}_3$ , respectively, and  $A_F$  is atom%  $^{15}\text{N}$  excess (4.6337) of the applied SF.

The effects of compost and SF types and their interaction on soil pH and  $\text{NH}_3$  volatilization were statistically evaluated via analysis of variance using the general linear model procedure of the SPSS 15.0 package (SPSS Inc., Chicago, IL) for a completely randomized design with three replications. When the

treatment effects were significant, the means were separated via Duncan's multiple range test. The significance level for all statistical tests was set at  $\alpha=0.05$ .

## Results

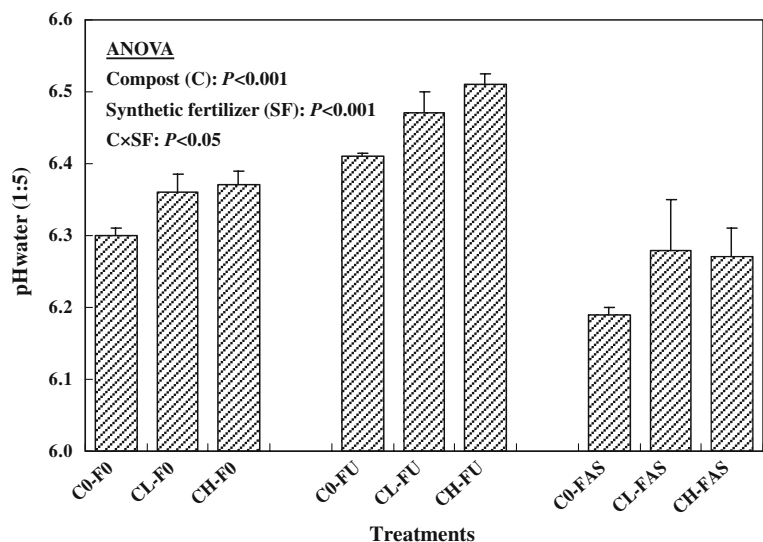
### The pH of soil mixtures

Application of composts (both CL and CH) significantly ( $P<0.001$ ) increased soil pH regardless of SF co-application (Fig. 1). For example, application of CL increased soil pH from 6.30 (C0-F0) to 6.36 (CL-F0) and CH increased it to 6.37 (CH-F0) in the soils without SF application. The effect of SF application on soil pH was also significant ( $P<0.001$ ) regardless of compost application; e.g. urea application increased soil pH from 6.30 (C0-F0) to 6.41 (C0-FU) but ammonium sulfate decreased it to 6.19 (C0-FAS) in the soils without compost. There was a significant ( $P<0.05$ ) interaction between compost and SF applications, resulting in the highest soil pH in CH-FU followed by CLFU > COFU > CHF0 = CLF0 > C0F0 = CLFAS = CHFAS > C0FAS.

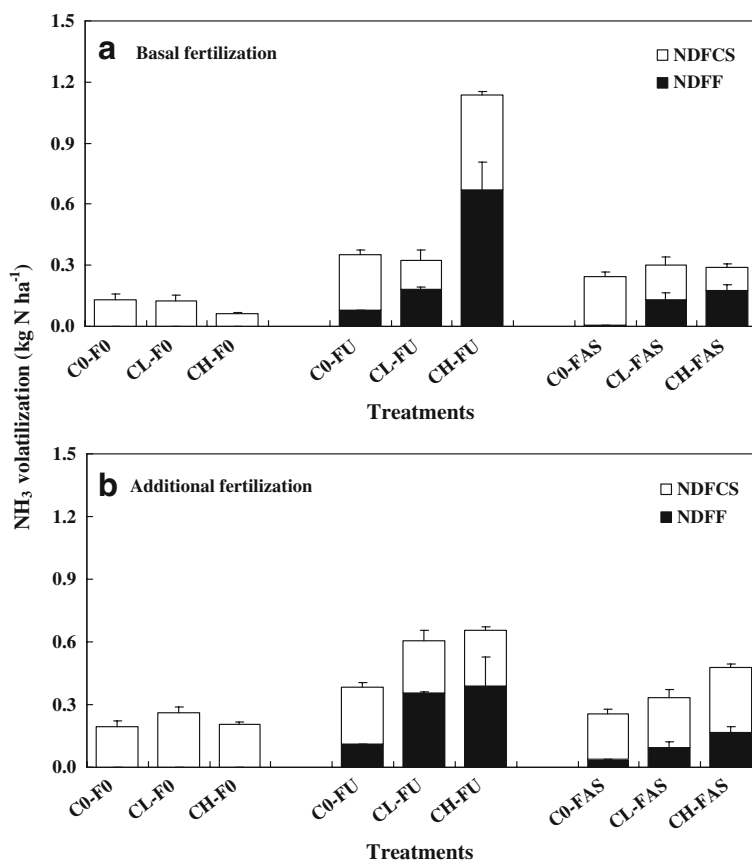
### $\text{NH}_3$ volatilization from basal fertilizer

The total amount of  $\text{NH}_3$  volatilization ( $\text{total}_{\text{NH}_3}$ ) during the first 10 days after the basal fertilization in the treatments without SF were 0.13, 0.12, and 0.06 kg N  $\text{ha}^{-1}$  for C0-F0, CL-F0, and CH-F0,

**Fig. 1** The effects of compost and synthetic fertilizer types on pH of soil 24 hrs after their application. Details of the treatments are shown in Table 2. Vertical bars are standard errors of the means ( $n=3$ ). ANOVA results are given



**Fig. 2** The effects of compost and synthetic fertilizer types on total  $\text{NH}_3$  volatilization (the sum of NDFF and NDFCS, if applicable), NDFF (volatilized N derived from synthetic fertilizer), and NDFCS (volatilized N derived from compost and/or soil) during 10 days after basal and additional fertilization. Details of the treatments are shown in Table 2. Vertical bars are standard errors of the means ( $n=3$ )



respectively (Fig. 2a). Application of SF resulted in a significant increase of total $\text{NH}_3$  by more than 2-fold with different magnitudes, owing to the effects of compost and SF types (Fig. 2a), and we noted a significant interaction between compost and SF (Table 3). The total $\text{NH}_3$  in the ammonium sulfate-treated soils did not differ between the treatments (0.24, 0.30, and 0.29 kg N ha<sup>-1</sup> for C0-FAS, CL-FAS, and CH-FAS, respectively). Meanwhile, in the urea-treated soils, co-applied CL did not affect total $\text{NH}_3$  (0.35 kg N ha<sup>-1</sup> in C0-FU and 0.33 kg N ha<sup>-1</sup> in CL-

FU), but CH caused a significant increase in total $\text{NH}_3$  to 1.14 kg N ha<sup>-1</sup> in CH-FU, resulting in the highest level of  $\text{NH}_3$  volatilization among all the treatments (Fig. 2a).

The amount of  $\text{NH}_3$  volatilization of NDFF applied as a basal fertilizer was also affected significantly by the interaction between compost and SF types (Table 3). The co-application of compost resulted in a substantial increase in the  $\text{NH}_3$  volatilization of N from ammonium sulfate by a factor of more than 10 (0.13 and 0.18 kg N ha<sup>-1</sup> in CL-FAS and CH-FAS,

**Table 3** Analysis of variance (only  $P$ -values are shown) testing the effects of synthetic fertilizer (SF) and compost types (Compost), and their interactions on total  $\text{NH}_3$  volatilization

Sources of effects	Basal fertilization			Additional fertilization		
	Total	NDFF	NDFCS	Total	NDFF	NDFCS
Compost type (Compost)	<0.001	<0.001	0.031	0.004	0.001	0.344
Synthetic fertilizer type (SF)	<0.001	<0.001	<0.001	<0.001	<0.001	0.193
CompostxSF	<0.001	<0.001	<0.001	0.127	0.008	0.181

rate, NDFF (volatilized N derived from SF), and NDFCS (volatilized N derived from compost and/or soil)

respectively), as compared with the treatment without compost (C0-FAS, 0.01 kg N ha<sup>-1</sup>) (Fig. 2a). However, the difference between CL-FAS and CH-FAS was not statistically significant. In the urea-treated soils, the co-application of CL increased the NH<sub>3</sub> volatilization of NDFE from 0.08 in C0-FU to 0.18 kg N ha<sup>-1</sup> in CL-FU, and the co-application of CH further increased the NH<sub>3</sub> volatilization of NDFE to 0.67 kg N ha<sup>-1</sup> (Fig. 2a). The percentages of NH<sub>3</sub> volatilization relative to the applied SF (110 kg N ha<sup>-1</sup>) were 0.07% for C0-FU, 0.16% for CL-FU, and 0.61% for CH-FU in the urea treatments and 0.01% for C0-FAS, 0.12% for CL-FAS, and 0.16% for CH-FAS in the ammonium sulfate treatment.

Not only the NH<sub>3</sub> volatilization of NDFE, but also that of NDFCS, was affected significantly by interaction between compost and SF types. In the urea treatment, the NH<sub>3</sub> volatilization of NDFCS was reduced via CL application, but increased by the application of CH. Meanwhile, the NH<sub>3</sub> volatilization of NDFCS was reduced by the co-application of compost in the ammonium sulfate treatments, regardless of compost type, as compared with treatments without compost (Fig. 2a).

#### NH<sub>3</sub> volatilization from additional fertilizer

The overall patterns of total<sub>NH<sub>3</sub></sub> and NH<sub>3</sub> volatilization of NDFE as affected by compost and SF type application did not differ between basal and additional fertilizations (Fig. 2b). However, the higher volatilization of NH<sub>3</sub> as the result of co-application of CH over the co-application of CL in the urea treatment observed in the basal fertilization was not detected after additional fertilization (Fig. 2b). Meanwhile, the NH<sub>3</sub> volatilization of NDFCS was affected neither by compost nor by SF type (Table 3). The percentages of volatilized N from applied SF (300 kg N ha<sup>-1</sup>) as an additional fertilizer became lower than that as a basal fertilizer (Fig. 2b); 0.04% for C0-FU, 0.12% for CL-FU, and 0.13% for CH-FU in the urea treatments and 0.01% for C0-FAS, 0.03% for CL-FAS, and 0.06% for CH-FAS in the ammonium sulfate treatments.

## Discussion

In our study, the percentages (less than 1.0%) of N loss as NH<sub>3</sub> volatilization relative to applied SF were

small as compared with other studies. For example, Bouwman et al. (1997) reported that the percentages of NH<sub>3</sub> loss from SF applied to paddy, upland, and grassland were 20, 14, and 6% of applied SF, respectively. The substantially low NH<sub>3</sub> volatilization from SF in our study was probably attributable to the experimental conditions that can reduce NH<sub>3</sub> volatilization potential. For example, in our study, SF was applied as a solution that allows for the rapid downward movement of applied N below the soil surface, minimizing the direct emission of NH<sub>3</sub> from the surface. The closed chamber method adopted in our study might also contribute to the low level of NH<sub>3</sub> volatilization by preventing the wind-driving mass flow of NH<sub>3</sub> gas (Bouwman et al. 2002). However, as all the treatments were subjected to the same experimental conditions in our study, the difference in NH<sub>3</sub> volatilization observed among the treatments could be assumed to reflect the effects of compost and SF types, as intended.

In our study, compost application resulted in an increase in the NH<sub>3</sub> volatilization of NDFE for both urea and ammonium sulfate regardless of the compost type, as compared with the treatments (C0-FU or C0-FAS) without compost (Fig. 2). This can be attributed to the high pH of the compost itself (over 8.0) (Table 1), because application of compost with a higher pH than soil can increase soil pH (Fig. 1) particularly for acid soil (Whalen et al., 2000) and the increased pH directly influences the equilibrium between NH<sub>4</sub><sup>+</sup> and NH<sub>3</sub> (Fenn and Hossner 1985; Gil et al. 2008). However, the magnitude of the NH<sub>3</sub> volatilization of NDFE was affected significantly by the interaction between compost and SF types, and this was more pronounced for basal than for additional fertilization (Table 3). For basal fertilization, the NH<sub>3</sub> volatilization of NDFE in the ammonium sulfate-treated soils did not differ between CL-FAS and CH-FAS; however, in the urea-treated soils, the application of CH resulted in a significant increase in NH<sub>3</sub> volatilization over CL application (Fig. 2a), thereby suggesting that another factor influences NH<sub>3</sub> volatilization besides compost pH. Because the properties of CH and CL were quite similar to each other, with the exception of urease activity (Table 1), the observed difference between CL-FU and CH-FU could be attributed principally to higher urea hydrolysis potential in CH than in CL-treated soils. Therefore, in combination with the high pH of

compost, the high urease activity in CH (Table 1) appeared to enhance  $\text{NH}_3$  volatilization in CH-FU by increasing soil pH over CL-FU (Fig. 1).

The  $\text{NH}_3$  volatilization patterns observed in our study imply that the co-applications of compost and synthetic fertilizer could substantially enhance  $\text{NH}_3$  volatilization, particularly in cases in which the compost had high urease activity and urea was co-applied as a basal fertilizer in spite of the high CEC of the composts (Table 1). The effect of the co-application of compost with urea on the urea hydrolysis rate, soil pH, or  $\text{NH}_3$  volatilization has rarely been investigated. In a laboratory incubation study, Choi et al. (2007) reported that increasing application of compost significantly enhanced urea hydrolysis; the 1<sup>st</sup> order rate constant of urea hydrolysis increased from  $0.047 \text{ h}^{-1}$  in the soil without compost, to  $0.139 \text{ h}^{-1}$  in the soil with compost at  $14.6 \text{ g kg}^{-1}$ . Accordingly, compost application increased the soil pH from 7.0 to 7.6, resulting in a greater  $\text{NH}_3$  volatilization. As far as we know, our study is the first report on such an effect of compost co-application on  $\text{NH}_3$  volatilization from urea-treated soils with a crop. In a similar fashion, the higher  $\text{NH}_3$  volatilization of NDFCS in CH-FU treatment as compared with the others could also be attributed to an elevation of soil pH resulting from the co-application of urea and compost containing high urease activity (Fig. 1), which is generally favorable for the  $\text{NH}_3$  volatilization of compost and/or soil derived  $\text{NH}_4^+$  (Bremner 1995; Bouwman et al. 2002). Therefore, the results of our study indicate that the co-application of compost evidencing high urease activity with urea as a basal fertilizer can increase the  $\text{NH}_3$  volatilization of N, not only from co-applied urea but also from compost and/or soil.

On the other hand, the co-application of CH with ammonium sulfate increased  $\text{NH}_3$  volatilization neither from ammonium sulfate nor from soil and/or as compared with co-application with CL (Fig. 2a), thereby suggesting that ammonium sulfate is a better alternative to urea as a basal SF when co-applied with compost evidencing high levels of urease activity. This is due to the fact that ammonium sulfate is a slightly acidic compound, leading to decrease in soil pH (Fig. 1). It is also worthy of note that the co-application of compost significantly reduced the  $\text{NH}_3$  volatilization of NDFCS except for CH-FU as compared with soils treated only with SF (Fig. 2a).

This result implies that a more optimal combination of compost and SF types may certainly reduce  $\text{NH}_3$  volatilization not only from SF, but also from compost and/or soil. Such a beneficial effect of the co-application of compost on  $\text{NH}_3$  volatilization could be explained by the immobilization of indigenous soil  $\text{NH}_4^+$ , which would otherwise be susceptible to  $\text{NH}_3$  volatilization. As the immobilization of N is generally determined by the quantity of decomposable C for heterotrophs, the application of compost with high organic matter contents might enhance the immobilization and thus reduce the possibility of the  $\text{NH}_3$  volatilization of indigenous soil N (Hadas et al. 1996; Choi et al. 2001). For CH-FU treatment, however, the effect of soil pH elevation as the result of enhanced urea hydrolysis likely prevailed against such a beneficial effect of compost application on reducing  $\text{NH}_3$  volatilization via  $\text{NH}_4^+$  immobilization (Fig. 2a).

As compared with basal fertilization, the  $\text{NH}_3$  volatilization of additional fertilization evidenced different patterns from two viewpoints. First, the percentage of volatilized  $\text{NH}_3$  from SF relative to the applied N as an additional fertilizer (rate:  $300 \text{ kg N ha}^{-1}$ ) became generally smaller than that used as a basal fertilizer ( $110 \text{ kg N ha}^{-1}$ ); the most pronounced reduction was observed in the case of CH-FU treatment (Fig. 2). Such a decrease, particularly in CH-FU, could be attributed principally to diminished urease activity with time after compost application (Piotrowska et al. 2006). Zaman et al. (1999) also determined that urease activity in soils treated with dairy shed effluent was reduced by half at 30 to 42 days after application in an incubation study. Accordingly, the  $\text{NH}_3$  volatilization of NDFCS in CH-FU after additional fertilization was reduced as compared with that observed after basal fertilization. The patterns of  $\text{NH}_3$  volatilization of the additionally applied SF indicate that the time difference between compost and urea application is also a crucial factor in the control of the  $\text{NH}_3$  volatilization of applied urea. The other different pattern of  $\text{NH}_3$  volatilization between basal and additional fertilization involves the effect of compost application on the  $\text{NH}_3$  volatilization of NDFCS (Fig. 2). Unlike basal fertilization, compost application did not diminish the  $\text{NH}_3$  volatilization of NDFCS within the same SF treatment, with the exception of CH-FU. This result may be attributable to the fact that compost is heterogenous, consisting of more than two organic C



components decomposing at different rates, as suggested by Hadas et al. (1993) and Choi et al. (2001). After the exhaustion of easily decomposable C during the early period, the contribution of the microbial immobilization of  $\text{NH}_4^+$  to the reduction of  $\text{NH}_3$  volatilization may prove less significant. Choi et al. (2006) demonstrated a very rapid exhaustion of readily decomposable organic-C (glucose) within 1 week, followed by a swift release of  $\text{NH}_4^+$  via re-mineralization.

In conclusion, three fertilization strategies to reduce  $\text{NH}_3$  volatilization when compost and SF are co-applied are suggested in this study. The first of these involves the use of compost with relatively low urease activity when urea is co-applied with compost. The second involves the use of ammonium sulfate as a SF when information regarding the urease activity of compost co-application is not available. The third involves the application of compost as basal fertilization in combination with the delayed application of urea as an additional fertilizer. The final strategy may be the most feasible of these practices, as compost is likely to have inherently high urease activity, and urea is the most widely employed fertilizer in the world.

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