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Full Length Research Paper

Combining compost with urea: Nitrogen and phosphorus recovery by cabbage and leaching under imposed high rainfall condition in the greenhouse

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Data from one cabbage growing season was used to compare nitrogen (N) and phosphorus (P) recovery and leaching between independent and combined application of composted manure and urea in the greenhouse. Treatments included: chemical-fertilizer (NPK at 250:80:150 kg ha^{-1}, respectively), organic-fertilizer (250 kg N from 16 Mg ha^{-1} of compost), low-combination (125 kg N from urea and 125 kg N from 8 Mg ha^{-1} of compost), high-combination (double of low-combination), and a blank control. Nitrate-N (NO_3) and inorganic water soluble P (WSP) leaching were monitored fortnightly. Organic and chemical fertilizer treatments suffered from demerits of low N recovery (9.34%) and high NO_3 leaching (27%), respectively. While cumulative NO_3 leaching loads in both low-, and high-combination treatments were low, high-combination treatment demonstrated greater numismatic quality by outperforming low-combination treatment by higher retention and uptake of N and P. Taking into account the prevailing environment the soil represents to, 16 Mg ha^{-1} of compost co-applied with 250 kg urea-N appears to be more appropriate combination for cabbage growth. Although WSP leaching was negligible, water quality benefits from this compost application does not seem to be promising, especially because other forms of P leaching (organic and/or inorganic) was suspected which warrants further study.

Key words: Composted manure, urea, nitrogen and phosphorus recovery, leaching, fertilization.

INTRODUCTION

Growing environmental concerns and comparative advantages drive much of our research endeavors in choosing chemical and organic fertilizers for crop production. Taiwan's government regulations encourage farmers to apply composted manure to ease the disposal problem of industrial manure (approximately 31507 Mg day^{-1} from swine, goat and cattle collectively) (Yang, 2005). While manure and composted manure offer an economical source of nutrients, mismanagement of these could lead to substantial N losses prior to crop uptake (Sullivan et al., 2005). This prompted research to obtain knowledge on leaching and crop recoveries of compost-applied N and P. The dilemma is that not all the N and P applied through organic fertilizers are plant-available. As a result, more N and P are applied to meet the crop requirements (Beegle et al., 2008) which can buildup total N, NO_3-N and P levels in soil affecting nutrient economy and water quality (King et al., 1985; Nelson et al., 2005; Sharpley et al., 1996). This ultimately requires lower levels of compost application and use of supplemental fertilizer to meet crop requirement while avoiding costly surplus of N and reducing P buildup in the soil (Sikora and Enkiri, 2001).

Taiwan was one of the heavy users of chemical fertilizers in the past (Ahmed, 1994). As a result, soil nutrient balance in high rainfall areas changed and soils were degraded due to nutrient leaching 'particularly the N' (Huang, 1994). There has been an increasing trend of composted manure application in Taiwan's farmlands, but

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Table 1. Initial characteristics of soil and compost used.

Measured properties	Unit	Soil	Compost
Texture	-	Sandy clay loam	-
Sand	g kg^{-1}	475	-
Silt	g kg^{-1}	266	-
Clay	g kg^{-1}	249	-
Soil and compost pH	-	4.5	6.9
Electrical conductivity	dS m^{-1}	0.6	2.5
Total nitrogen (N)	g kg^{-1}	1.40	37.3
Inorganic N	mg kg^{-1}	13.1	2009
Organic carbon (C)	g kg^{-1}	13.8	420
Total phosphorus (P)	g kg^{-1}	0.50	36.3
Water soluble P	mg kg^{-1}	18.4	2700
Bray-1 P	mg kg^{-1}	29.9	-
Total potassium	g kg^{-1}	5.60	3.80
Total zinc	mg kg^{-1}	-	92.7
Total copper	mg kg^{-1}	-	28.4

Soil pH by 1:1 soil/water ratio, compost pH by 1:5 compost/water ratio (w/w).

most research focused on food production and hence information concerning environmentally sensitive aspects such as NO_3-N and P leaching in conjunction with crop recovery of applied N and P are less documented.

Although difficult, part of the N and P leaching problem arises due to our inability to establish crop recoveries to help regulate application of organic fertilizers. Globally, N use efficiency of chemical fertilizer is about 50% (Eickhout et al., 2006), whereas N mineralization in compost varies greatly. For example, He et al. (2000) observed 23.5% mineralization in 1st-y field incubation of compost, whereas Passoni and Borin (2009) reported from 0 to over 50% in the 1st growing season indicating that existing literature is not clear on this point. However, availability of N and P from compost-applied soils can be measured directly using crop uptake in pot and field experiments (Eghball, 2002).

A great diversity exists in N availability (2 to 44%) in compost (Eghball and Power, 1999; Iglesias-Jimenez and Alvarez, 1993; Kirchmann, 1990; Larney et al., 2006). Although variability of crop N recovery from manure and compost is often due to variability in the composition of the organic materials itself, low crop N recovery and high leaching have also been largely attributed, among others, to the independent application of organic and chemical fertilizers (Aronsson et al., 2007; Beegle et al., 2008; Esteller et al., 2009; Maeda et al., 2003). Grounded on these demerits of independent application of organic and chemical fertilizers, this study attempts to evaluate combined application assuming that the mixture would provide so-called numismatic qualities in terms of measured variables. We are not asking new questions but trying to see if we can provide new answers. The concept of organic farming discourages the usage of chemical fertilizers but through the time, complete stoppage also became impractical for fear of inadequate and slow supply of nutrients from mere application of organic materials. It then, continues to explore a win-win situation to capture the merits of both organic and inorganic systems, which is possible only through the combined application. This is what we meant from the term ‘numismatic value’ in this paper. However, diverse research results suggest the need for identifying and establishing combinations appropriate to a particular situation.

Earlier reports have found both positive and negative effects on crop recovery and leaching due to choices of organic and chemical fertilizations. Thus, the objectives of this study were to examine the important combinations of chemical and organic fertilizers versus independent application for apparent crop recovery of N and P, and leaching of NO_3-N and inorganic WSP under imposed high rainfall and severe leaching conditions in the greenhouse.

MATERIALS AND METHODS

Sample preparation

Soils representing the surface 0-15 cm were sampled from the leveled upland agricultural area of Taoyuan (29°59' N and 121°02' E) located in Northern part of Taiwan. The sampling area possesses hot (average monthly temperatures of 15 to 29°C) and humid (> 2000 mm average annual rainfall) weather dominated with coarse textured soils overlying shallow ground water tables. Soil belongs to Sankengtzu series and is classified as Entisol Soil Order (or Typic Udifluvent Subgroup) based on Soil Taxonomy,

Table 2. Quantities of compost, Urea, MCP, KCl and nutrients applied to treatments before cabbage planting in April, 2006.

Nutrient source	Treatment†				
	Control	Chemical- fert	Organic- fert	Low-comb	High-comb
	------------------------------ g pot^{-1} ------------------------------				
Compost	0	0	80	40	80
N from compost	0	0	2.5	1.25	2.5
P from compost	0	0	2.42	1.21	2.42
Urea	0	2.71 (1.25) ¶	0	1.30 (0.62)	2.71 (1.25)
Mono-calcium phosphate (MCP)‡	0	0.71 (0.40)	0	0	0
Potassium chloride(KCl)‡	0	1.20 (0.80)	0.60 (0.40)	0.90 (0.60)	0.60 (0.40)

†Chemical-fert = Chemical fertilizer (recommended rate of NPK, 250:80:150 kg ha^{-1}, respectively, N from urea), Organic-fert = Organic fertilizer (250 kg N from 16 Mg ha^{-1} of compost), Low-comb = Low combination (125 kg N from urea + 125 kg N from 8 Mg ha^{-1} of compost), High-combination (double of low combination). Assumed rate of N mineralization during growing season in compost = 50%. Organic-fert and high-comb treatments each oversupply 66 kg P, but low-comb treatment undersupply 7 kg P ha^{-1} relative to recommended 80 kg P ha^{-1} assuming 30% P release rate in compost. ¶Values in parenthesis indicate elemental nutrients, not the fertilizer. Wagner pots contained 12.8 kg of soil on dry weight basis. ‡MCP and KCl are reagent grade chemicals.

Department of Agriculture, United States of America (USDA). Soil samples were air-dried, mixed and passed through a 2 mm sieve. Initial physical and chemical properties of soil are shown in Table 1. Soils were analyzed for sand, silt, and clay contents by pipette analysis following dispersion by sodium hexametaphosphate (Gee and Bauder, 1986). The standard Wagner pots (30 cm high and 25 cm diameter) were filled with approximately 22 cm deep soil column (12.8 kg, dry weight basis) which allowed space for holding the added water for conducting leaching test. At the time of pot-filling, soil was pounded against the ground in order to settle the mix thoroughly.

Compost (Product Registration Number 0237001 Taiwan Council of Agriculture) was obtained from Chia-Yi County Compost Plant located in southern Taiwan. It was made from swine manure and mushroom growing media (5:1 by volume). Mushroom growing media had 95% wood flour and 5% cereal flour. Air-dried compost samples were passed through a 10 mesh screen. According to our own analysis, compost samples had total N (37.3 g kg^{-1} on dry wt. basis), total P (36.3 g kg^{-1} on dry wt. basis) and C:N ratio 11.3. Results of detailed compost sample analysis are shown in Table 1. Total copper and zinc concentrations digested with aqua regia for the compost were found within the permissible limits (100 mg kg^{-1} for Cu, and 500 mg kg^{-1} for Zn) as regulated by Taiwan Council of Agriculture (2010) for crop production.

Experimental design

The experiment was conducted in the greenhouse of National Taiwan University, Taipei from April to August of 2006. Treatments included: (i) chemical fertilizer, applied recommended rate of NPK at 250:80:150 kg ha^{-1} from urea, mono-calcium phosphate (MCP) and potassium chloride (KCl), respectively, (ii) organic fertilizer, applied 250 kg N from 16 Mg ha^{-1} of compost, (iii) low-combination, applied 250 kg N, one-half each from urea and 8 Mg ha^{-1} of compost, (iv) high-combination, applied 500 kg N, one-half each from urea and 16 Mg ha^{-1} of compost, and (v) zero control for comparison. For discussion, these treatments are hereafter abbreviated as Chemical-fert, Organic-fert, Low-comb, High-comb and control, respectively. Actual amounts of compost, urea, MCP and KCl (g pot^{-1}) applied are shown in Table 2. All treatments were replicated four times, completely randomly attributed to 20 Wagner's pots. With four pots per table, 20 pots were then put on five movable tables (76 cm high X 69 cm wide X 76 cm long). Pots were kept in the corners of each table to reduce plant competition for sunlight during growth. Adjacent tables were kept at a distance enough for cultural or leaching operations.

Compost literature is not yet very clear on N mineralization rate (Passoni and Borin, 2009); therefore a liberal assumption of 50% N mineralization for the first growing season was made consistent with the previous cabbage research by Tzen and Chen (2004). Passoni and Borin (2009) also reported that N mineralization in compost can vary from 0 to over 50% in the first growing season. At 50% N mineralization rate, compost oversupplied 66 kg P ha^{-1} in each of organic and high-comb treatments and undersupplied 7 kg P ha^{-1} in low-comb treatment relative to 80 kg ha^{-1} of recommended P for cabbage. Phosphorus could not be kept low in organic-fert and high-comb treatments because N-based compost application design automatically added more P at 16 Mg ha^{-1} of compost in these treatments, which in turn was primarily due to higher P in compost. Nutrients were calculated on surface area basis and incorporated in the upper half-part of the Wagner pot. Since nutrient availability in this soil is constrained by soil acidity (pH 4.5) and accelerated leaching due to hot and humid environment, we applied all recommended NPK from external sources to increase the probability that crop growth is not affected by nutrient deficiency. Purchased from a private nursery, cabbage (*Brassica oleracea* L.) seedlings were transplanted at stage-II (4-5 leaf) on April 15, 2006 and grown at day and night temperatures of 30 and 25°C, respectively. In the greenhouse, light intensity varied between day (avg. intensity of 638 ± 488 µE) and night (avg. intensity 1.2 ± 0.01 µE) hours. With a mean of 91%, relative humidity varied from 81 to 100% within 24 h during cabbage growing season.

Monitoring of NO_3-N and inorganic WSP leaching

In order to facilitate the root growth, seedlings were thinned to one plant pot^{-1} and monitoring of leaching started from May 6, 2006 and stopped before crop harvest. The purpose was to separate the effects of time on leaching from those of treatments. Each time when soil was leached, 4.0 L of tap water was applied gently using a graduated plastic jug simulating soil saturation due to rainfall for about 2-h, volumes in excess of saturation received in a container below the Wagner's pots and ended the leaching test after the free-flow ceased practically. Volumes were then measured on a

Table 3. Effect of compost and urea combinations on nitrogen and phosphorus uptake and recovery by cabbage.

Treatment	N uptake	P uptake	N recovery	P recovery
	-----------mg plant^{-1}---------		% of added N in excess of control	
Control	286 ± 24 d[†]	33.4 ± 13 c	-	-
Chemical-fert	615 ± 95 bc	74.0 ± 2.4 c	26.3 ± 7.6 a	10.1 ± 0.6 b
Organic-fert	520 ± 39 c	346 ± 63 b	9.34 ± 1.5 b	12.9 ± 2.6 ab
Low-comb	751 ± 23 b	256 ± 82 b	24.9 ± 1.2 a	18.4 ± 6.8 ab
High-comb	1043 ± 162 a	521 ± 91 a	20.2 ± 4.3 a	20.1 ± 3.7 a
P > f[‡]	***	***	***	**
CV, %	14	25	22	26
LSD (0.05)	190	135	9.4	8.6

[†]Within a column, means followed by the same letter are not significantly different by Tukey test ($P = 0.05$). Values are means ± standard deviations. [‡]**, *** significant at the $p = 0.01$ and $p = 0.001$ probability levels, respectively. Cabbage was grown at the rate of one plant per pot. Root N and P uptake not determined. Wagner pots contained 12.8 kg of soil on dry weight basis. See Table 2 for treatment definitions.

calibrated plastic jug. For each observation, about 300 mL of outflow sample was collected in clean and dry plastic bottles. Outflow samples were filtered with Whatman No. 42 and refrigerated at 4°C before analyzing for N and P leaching within a week. NO_3 leached was analyzed by steam-distilling 10 mL sub-sample using MgO and Devarda alloy (Mulvaney, 1996) and inorganic WSP leaching was analyzed by taking 40 mL sub-sample (Murphy and Riley, 1962). The amounts of these were then quantified by multiplying concentrations in leachate outflow by leachate volumes. These fortnightly loads were then totaled to give the seasonal load of each N and P for each treatment.

Water added to cabbage for leaching corresponded to 2000 mm y^{-1} average annual rainfall of this region. Given the fortnightly leaching frequency in one year, this value corresponded to 2000/24 = 83.3 mm rainfall depths per time of leaching operation. Actual amount of water required for each leaching event (4.1 L pot^{-1}) was computed by multiplying annual rainfall by surface area of the Wagner's pot divided by 24 leaching frequencies in a year. In carrying out fortnightly leaching operation, we assumed that soils in this region receive uniform and frequent rainfall causing substantial amounts of nutrients leaching during summer cabbage season.

We must mention that dissimilarities between soil and pot surface characteristics show the possibilities of water channeling down the inner pot-wall. However, practices such as allowing time enough to saturate the soil before outflow begins, use of greater volume of soil, and proper attendance during the leaching events were found useful for reducing this problem.

Plant and soil chemical analysis

Sixteen weeks after transplanting, aboveground cabbage parts were harvested on August 17, 2006. Harvested plant parts were washed with deionized water, fresh weights taken, chopped into pieces and oven-dried (65°C for 4 to 5 days) to constant weight and dry weights recorded for N and P uptake. Plant samples were ground in a stainless steel mill and stored in plastic bags until analysis. Total N in soil and plant samples were determined by Kjeldahl digestion and steam distillation (Bremner and Mulvaney, 1982). Digested aliquot was also subject to spectrophotometry for quantifying P (Murphy and Riley, 1962). NO_3–N in soil was determined by using the method of Mulvaney (1996), total soil P using perchloric acid method (Kuo, 1996), and Bray-1 P by Bray and Kurtz (1945). These analyses were based on soil samples taken by thoroughly mixing and quartering the whole pot-soil. Due to relatively higher fraction of clay, soil samples were passed through 100 mesh screen for chemical analysis expecting that grinding samples at higher mesh could improve recovery of the measured soil parameters.

Cabbage recovery of N and P and data analysis

Apparent N and apparent P recovery (hereafter referred to as cabbage N recovery and P recovery) were calculated using 'difference method' following Motavalli et al. (1989) as below:

Apparent N recovery, % = [(N in treatment – N in control)/total N applied] x 100% (1)

Apparent P recovery, % = [(P in treatment – P in control)/total P applied] x 100% (2)

One-way ANOVA was used to test the significance of treatment effect on measured soil, crop and leachate parameters (SAS Institute, 2008). Treatment differences were compared using Tukey test ($p = 0.05$).

RESULTS

Cabbage uptake and recovery of N and P

Table 3 presents data on cabbage N and P uptake in relation to total applied N and P. Nitrogen uptake ranged between 286 and 1043 mg pot^{-1} and P uptake between 33.4 and 521 mg pot^{-1}. These corresponded to 0.8 to 2.6 fold higher N uptake and 1.2 to 14.6 fold higher P uptake in the treatment in comparison with the control treatment. The increases were significant except P uptake in chemical-fert treatment relative to the control treatment. High-comb treatment outperformed all other treatments in terms of increasing N and P uptake.

There were no significant differences in cabbage N recovery among chemical-fert (26.3%), low-comb (24.9%)

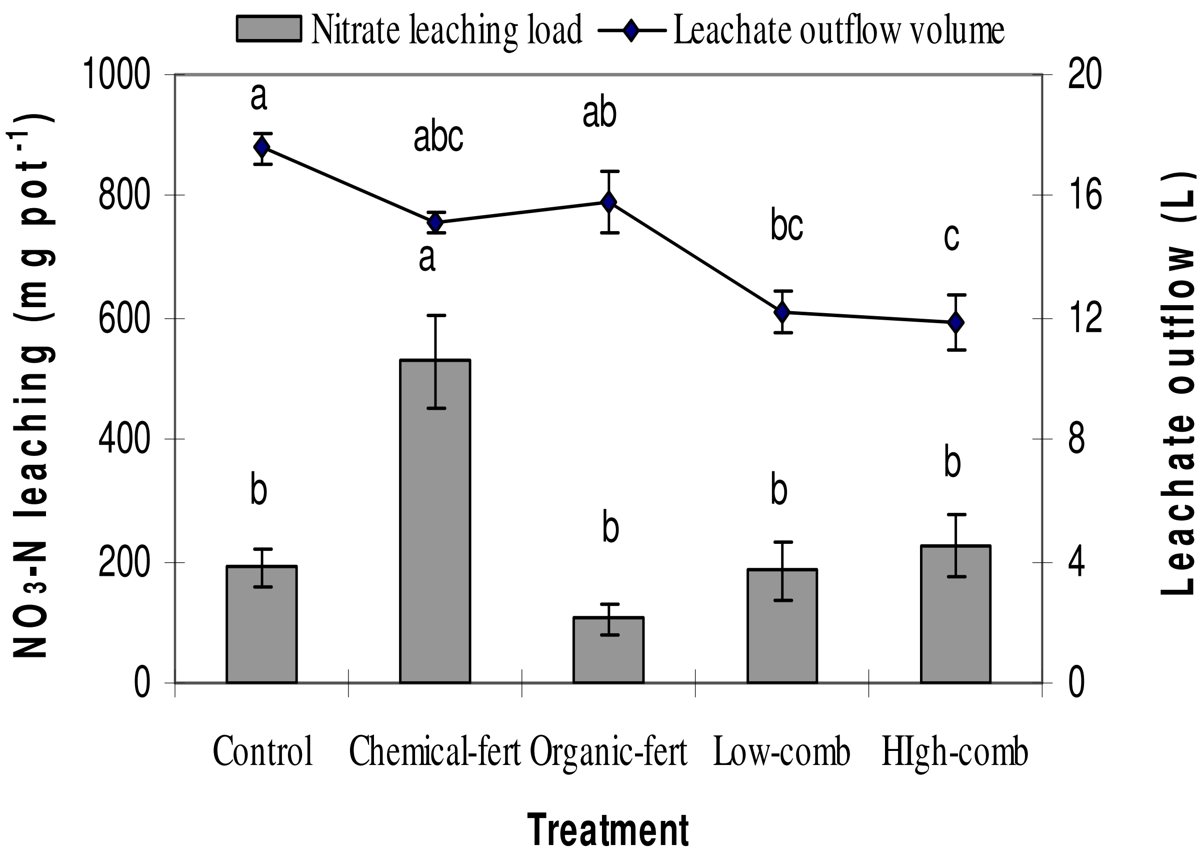

Figure 1. Effect of compost and urea application on cumulative NO_3-N leaching load and leachate outflow volume during cabbage growing season from May to August, 2006. Bar heights or points on a line followed by the same letter are not significantly different by Tukey test (P = 0.05). Error bars represent standard deviations. Values for a treatment indicate sum of 7 leaching monitoring dates.
See Table 2 for treatment definitions.

and high-comb (20.2%) treatments (Table 3) but the N recovery in organic-fert treatment (9.34%) was signify-cantly low. Likewise, cabbage P recovery increased 2 fold in high-comb treatment (20.1%) in comparison with the lowest recovery in chemical-fert treatment (10.1%). Cabbage P recovery in organic-fert and low-comb treatments were intermediate to both chemical-fert and high-comb treatments.

NO_3 and inorganic WSP loads and concentrations in outflow samples

Cumulative NO_3 leaching loads from 7 monitoring dates in organic, low-comb and high-comb treatments were statistically at par with the control (190 mg pot^{-1}), whereas it accelerated in chemical-fert treatment (528 mg pot^{-1}) (Figure 1). The greatest spikes of flow-weighted mean of NO_3 concentrations were observed during the first monitoring date where the mean value ranged from 49 mg L^{-1} in the control treatment to 98 mg L^{-1} in chemical-fert treatment (Figure 2). Concentrations then decreased sharply in all except the chemical-fert treatment where it maintained high and steady drop with time. High-comb treatment (50 mg L^{-1}) also showed high NO_3 concen-rations but it reduced sharply after the initial two leaching monitoring dates.

Cumulative inorganic WSP leaching loads were recorded in traces (2.72 to 3.15 mg pot^{-1}) and hence relatively insignificant with respect to the amount of P added. Due to smallness and mostly non-significant, WSP load data are not presented. Flow-weighted mean concentrations of WSP ranged between 0.04 and 0.58 mg L^{-1} (Figure 3).

NO_3 leaching loads by monitoring date and outflow volumes

The 1st leaching monitoring date produced 51% of the

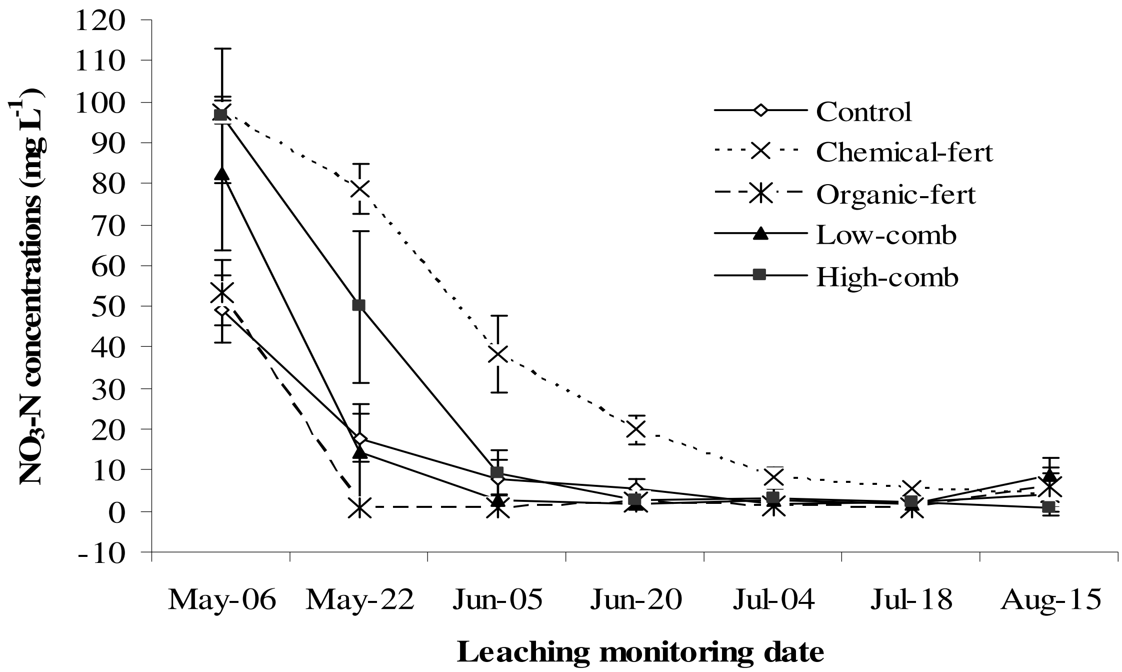

Figure 2. NO_3-N concentrations measured in leachate outflow water samples by leaching monitoring date during cabbage growing season from May to August, 2006. Error bars represent standard deviations. See Table 2 for treatment definitions

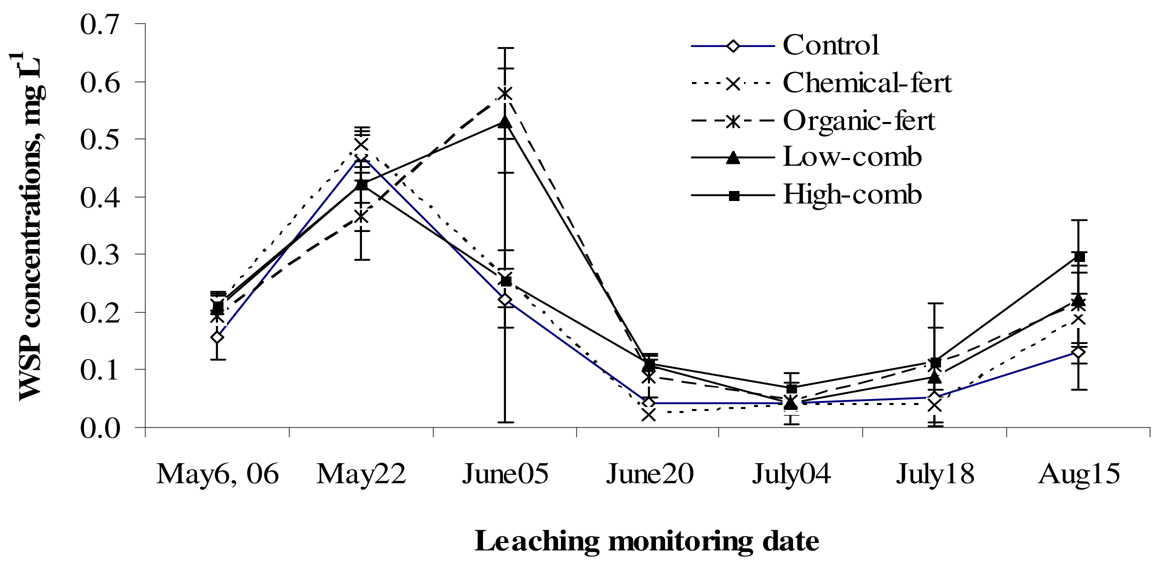

Figure 3. Inorganic water soluble P concentrations measured in leachate outflow samples by leaching monitoring date during cabbage growing season from May to August, 2006. Error bars represent standard deviations. See Table 2 for treatment definitions.

seasonal NO_3 leaching load flushed by 12% of the seasonal outflow volume (Figure 4). Chemical-fert treatment alone was accounted for about 32% of NO_3 leaching during the 1st monitoring date and 43% during the entire season, whereas leaching loads in other treatments were not significantly different from the control (15%). The control removed the highest cumulative outflow (63% of the added water), whereas high-comb treatment recorded the lowest outflow (43% of the added water) with no significant difference with low-comb treatment. Wilting of

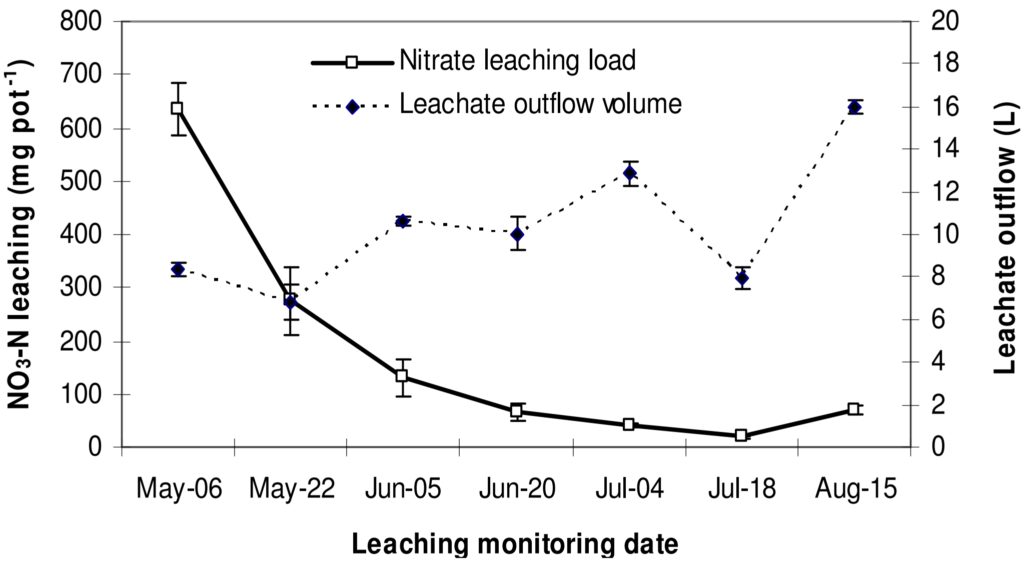

Figure 4. The trend of NO_3-N leaching loads and volume of leachate outflow by leaching monitoring date during cabbage growing season from May to August, 2006. For a given date, values in data points indicate sum of all five treatments. Error bars represent standard deviations.

cabbage leaves at head filling stage resulted in a marked increase in outflow volumes at 4th and 5th leaching dates in organic-fert treatment. Pest attack and temporary wilting of cabbage leaves after the 6th leaching date reduced water absorption and increased outflow volumes in all treatments during the 7th leaching date.

Total N, Total P, NO_3 and Bray-1 P in soil after cabbage harvest

Total N ranged between 16.8 and 19.7 g pot^{-1}, total P between 5.62 and 6.49 g pot^{-1}, NO_3 between 11.7 and 14.3 mg kg^{-1}, and Bray-1 P between 14.5 and 21.2 mg kg^{-1} (Table 4). Total soil N and total soil P in organic-fert and high-comb treatments were similar with each other but they were significantly ($p < 0.05$) higher compared with those in low-comb and chemical-fert treatments. Conversely, treatments were not different in terms of NO_3-N and Bray-1 P concentrations, except the high-comb treatment where Bray-1 P was significantly higher than in control treatment.

DISCUSSION

Relationships between cabbage N recovery, NO_3 leaching, and N retention in soil

Since approximately 90% of applied N was found retained in soil, < 10% cabbage N recovery in organic-fert treatment (Table 3) resulted from over assumption of 50% N mineralization rate in this compost. Cabbage N recoveries improved in low- and high-comb treatments with no significant differences with each other, but in absolute term, crop N uptake was especially greater in high-comb treatment. The difference occurred largely due to the variation in N availability expression.

Low crop N recoveries from compost application have also been reported in various literatures. For example, 10% potentially mineralizable N in composted pig manure(Lin and Houng, 1995), 15% apparent N use efficiency in the field (Eghball and Power, 1999) and 2 to 15% plant N recovery with compost-amended soils in the pot study (Hartz and Giannini, 1998). The N mineralization < 15% in 32-wk was regarded 'low' in compost (Hadas and Portnoy, 1994). In view of these literatures, low crop N recovery in organic-fert and high cumulative NO_3 leaching in chemical-fert treatment illustrated major demerits associated with independent application of compost and urea fertilizers (Table 3 and Figure 1). Results are consistent with our assumption and others including Herai et al. (2006) and Munoz et al. (2008) which led us to evaluate combinations of these assuming that when they are combined, the merits outweigh demerits. Underlying expectation was that the combining process adds so-called numismatic value that vastly exceeds the value of the fertilizers if applied independently. A significant improvement in crop N recovery without appreciable increases in NO_3 leaching in compost and urea combined treatments was because the combination triggered incredible things in the mixture.

Table 4. Effect of compost and urea combinations on total N, total P, NO_3-N, and Bray-1 P in soil after cabbage harvest during August, 2006.

Treatment	Total soil N	Total soil P	NO_3-N in soil	Bray-1 P
	------------g pot^{-1}----------		------------mg kg^{-1} soil--------	
Control	16.8 ± 0.4 b†	5.62 ± 0.1 c	11.7 ± 7.64 a	14.5 ± 1.39 b
Chemical-fert	17.3 ± 0.9 b	5.98 ± 0.1 b	14.3 ± 5.48 a	17.1 ± 1.88 ab
Organic-fert	19.1 ± 0.3 a	6.55 ± 0.1 a	12.5 ± 4.10 a	18.7 ± 0.63 ab
Low-comb	17.4 ± 0.6 b	5.96 ± 0.1 b	13.2 ± 3.37 a	16.4 ± 2.49 ab
High-comb	19.7 ± 0.6 a	6.49 ± 0.2 a	13.6 ± 5.78 a	21.2 ± 4.74 a
P > f‡	***	***	NS	*
CV, %	3.3	2.2	42	15
LSD (0.05)	1.31	0.29	11.9	5.75

†Within a column, means followed by the same letter are not significantly different by Tukey test ($P = 0.05$). Values are means ± standard deviations. ‡NS, *, *** not significant and significant at the 0.05 and 0.001 probability levels, respectively. Wagner pots contained 12.8 kg of soil on dry weight basis. See Table 2 for treatment definitions.

The findings are congruent with others including Sims (1987) and Jokela (1992) who observed reduced NO_3 leaching from compost-applied soils compared with equivalent N rates from chemical fertilizer. The overall NO_3 leaching is within the range (10-35%) observed by Toth et al. (2006).

Han et al. (2004) explains that urea blending with compost provides mineral-N for increased net mineralization of compost-N, more prominent in soils with relatively low organic-carbon. It also explains why low N recovery is observed in organic-fert treatments that do not receive chemical fertilizer. Recent advances in mineralization suggest that significant amount of organic-N is in complexly bonded polypeptide labile forms which make N slowly available (Olk, 2008). On top of this and irrespective of treatment types, frequent wetting of soil for leaching operations in this study would have affected microbial growth by creating a sub-optimal soil chemical environment for N transformation. Mineralization and nitrification are reduced in wet soils with moisture contents exceeding 33 kPa or field capacity (Tisdale et al., 1993). Limited cabbage root functions due to soil moisture above field capacity (Heuberger et al., 2002) also appear to have affected the microbial transformation of compost-N.

Post-plant differences between total soil N, uptake and leaching showed that soils retained approximately 42, 90, 33 and 77% of added N in chemical-, organic-, low-comb- and high-comb treatments, respectively (calculation not shown). These results indicate that while low crop recovery in chemical-fert treatment was primarily due to high NO_3 leaching, negligible NO_3 leaching in organic-fert and high-comb treatments was related to high soil retention because most of the applied N was in organic form. Reasons for low soil N retention in low-comb treatment were not apparent. Compost being a fairly stabilized product and due to low C:N ratio (Table 1), so-called extra decomposition “priming effect” was thought to be negligible. The small amount of N that was released during air-phase was probably utilized by growing cabbage plants. Therefore, bulk of organic N that is not mineralized and not lost by leaching contributes to organic N pool thereby increasing N availability to the succeeding crops. But it also can be a potential source of NO_3 in groundwater.

Relationships between crop P recovery, WSP leaching, and retained P in soil

Compost application (8 to 16 Mg ha^{-1}) with or without urea did not produce significant differences in cabbage P recovery among organic-fert, low-comb and high-comb treatments (Table 3). However, potential benefit of high-comb treatment was seen from significantly ($p < 0.05$) increased P recovery relative to that in chemical-fert treatment. Since chemical fertilizers enhance decomposition of soil organic matter (Chen, 2004) and rock phosphate also plays a role in composted manure (Singh and Amberger, 1991), greater increases in P uptake was partly due to adequate amount of urea-N and rock phosphate to accelerate P release and availability from the compost in high-comb treatment. Cabbage P recovery (18-20%) on low-, and high-comb treatments are in close agreement with Zvomuya et al., (2006) from composted cattle manure.

Given that most of the P in compost is inorganic (> 75%) (Eghball, 2003) and strongly acid soils have high P adsorption capacity, P availability in this study appears to have been largely related to desorption of inorganic P from compost. Some P release mechanisms are: (i) iron and aluminum combine with humic or organic acids released by decomposition of organic matter in compost (Barrow, 1989), and (ii) P adsorption sites become pre-occupied by organic P, and/or inorganic P ions dissolved from organic fertilizer or released by the mineralization of organic P fraction (Chen, 1996). P uptake was well correlated with Bray-1 P (r = 0.74, p < 0.01).

Post-plant differences between total soil P, uptake and inorganic WSP leaching showed that soil retention of P in organic-fert (38%), low-combination (28.5%) and high-combination treatments (35.7%) were significantly lower than that in chemical-fert treatment (71%) (p < 0.001). The P retention in former three treatments remained non-significantly different from one another. It turned out that approximately one-half of added P (44 to 53%) could not be accounted for from these compost-applied soils (calculation not shown). Although inorganic WSP load in leachate water samples was negligible (cumulative < 3.15 mg pot^{-1}), we believe that other forms of P leaching (organic and, or inorganic) occurred from these treatments at alarming rate which warrants for further study. Particulate P associated with sediment losses can be the main route for P loss from some soils. Negligible inorganic WSP leaching was attributed primarily to low inorganic WSP in the compost (7.5% of total P, result obtained by shaking of compost samples at 200 rpm for 1-h, centrifuged at 10,000 rpm for 10 min, followed by spectrophotometry, all glassware washed with 1M HCl). Results agree with Idowu et al. (2008) where large fraction of total P from cattle manure was leached as organic (63%) and greater percentage of total P was lost as inorganic in the soil amended with hog manure. It appears reasonable that frequent wet-phase of soil that reduced compost-N availability would have also been partly responsible for accelerated P leaching from this soil. Invariably high P leaching suspected from these treatments draws considerable concerns for examining total P for water quality and bioavailable (algal) P in the leachate outflow samples of this compost-applied soil.

Inorganic WSP is not the indicator of water quality and where P is used as an indicator, the forms of P and their threshold values vary with countries. For example, Taiwan Environmental Protection Administration (TWEPA) uses the criterion of total P (0.05 mg L^{-1}) for river and lake waters (http://law.epa.gov.tw/en/laws/309417667.html). TWEPA has not developed P regulations for drinking water and groundwater. For United States Environmental Protection Agency (USEPA), the level of concern of total P in water is 0.1 mg L^{-1} (van Es et al., 2004). As the WSP in this compost was only 7.5% of total P, the observed WSP concentrations (0.04 to 0.58 mg L^{-1}) in leachate outflow samples reflected the likelihood that leaching of total P in this compost-applied soil (although not monitored) would have been over the critical threshold for river and lake waters in Taiwan. The WSP concentrations observed in this study (Figure 3) closely agree with phosphate concentrations in leachate obtained by Esteller et al. (2009).

Relationships between outflow volumes and NO_3 leaching concentrations

Outflow volume was subject to the treatment variation; with the highest in the control which is consistent with previous report (Gaudreau et al., 2002). Contrarily, the lowest outflow volume in high-comb treatment appears to have resulted from compost and plant growth functions for increased water retention and absorption of more water (Lehrsch and Kincaid, 2007).

While the outflow volumes were not high, the peak flow-weighted NO_3 leaching concentrations in chemical-fert, low-comb and high-comb treatments on the 1st leaching date were significantly higher than that in the control and organic-fert treatments (Figure 2). The peak values correspond to those found by Esteller et al. (2009) in composted biosolids (4.5 Mg ha^{-1}), Miller et al. (2008) in beef manure compost (0, 13, 39, and 77 Mg ha^{-1} dry wt.) and Stoddard et al. (2005) in dairy manure (168 kg N ha^{-1}). It suggests that crop N recovery could be improved markedly if rainfall impacts were reduced early in the season after fertilization. Nevertheless, three patterns were distinguished: *one*, chemical-fert treatment where temporally distributed pattern of NO_3 leaching affected the crop N recovery, *two*, organic-fert treatment where leaching were always low, crop N recovery was not affected by such leaching, and three, low-and high-comb treatments being mostly similar with each other, only early 1-2 leaching dates affected crop N recovery. This led to emphasize that besides frequently reported timing of fertilization (Stoddard et al., 2005), volume of drainage outflow (Aronsson, et al., 2007), and the form of N (Esteller et al., 2009), temporal leaching behavior by nutrient source might also be important aspect of compost management strategy.

Temporal NO_3 leaching trend in chemical-fert treatment might serve as a new research question identified during this study. The trend reflects the effects of the method of treatment application, soil texture, disturbed soil structure and strong soil acidity favoring slowed urease activity for nitrification of urea-N. To a certain extent, this trend contradicts with Christianson et al. (1993) and Van Kessel et al. (2000) where nearly all of the urea hydrolysis and N release occurred within a week of application in acid soils (pH 5.2). More importantly, the results illustrate the significance of unique local conditions dictating the leaching behavior of this soil despite readily availability of mineral N in urea for leaching or crop uptake (Munoz et al., 2003). Nitrate leaching concentrations reduced to TWEPA and USEPA drinking water standard of 10 mg L^{-1} after the 1st leaching monitoring date in most cases except chemical-fert treatment. TWEPA standard of 10 mg L^{-1} relates to groundwater in drinking water source protected areas. But related to surface water sources, the revised TWEPA Article 3 of January 2, 2008 has set much lower standard

(0.10 mg L^{-1}). A comparison of results with this standard showed that NO_3 leaching concentrations in all treatments including the control exceeded the permissible limit throughout the monitoring dates. It was attributed primarily to the effects of water used to induce leaching representing high rainfall condition and to continued N mineralization in the soil.

Conclusion

Independent application of compost reduced cabbage N recovery and urea accelerated NO_3 leaching. Conversely, significant increases in cabbage N recovery with little or no increases in NO_3 and inorganic WSP leaching loads were seen as merits of combined application of these fertilizers.

While there were similarities in crop recovery and leaching loads of N and P, discernible difference were also observed between low- and high-comb treatments such as higher N and P uptake as well as higher total soil N and total soil P in high-comb treatment. The differences occurred due to adequate supply of N and P in high-comb treatment. From low-comb treatment, residual effect of N was not apparent. Therefore, an application of 16 Mg ha^{-1} of compost plus 250 kg of urea is suggested for cabbage under the condition of this experiment.

But it also seems unlikely to achieve water quality benefit accruing from this compost because a large fraction of added P was suspected to have leached as organic and/or inorganic which warrants further study. The frequent wet-phase of soil that reduced compost-N availability would have also been responsible for ace-lerated P leaching. A confirmatory field-scale study would be helpful especially for total P and algal P analysis.

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