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Nitrogen release and plant available nitrogen of composted and un-composted biosolids

Olawale Oladeji[1*] Guanglong Tian[1*] Pauline Lindo[1] Kuldip Kumar[1*] Albert Cox[1*] Lakhwinder Hundal[2*] Heng Zhang[1*] Edward Podczerwinski[1*]

[1]Monitoring and Research Development, Metropolitan Water Reclamation District of Greater Chicago, Cicero, Illinois
[2]InNow LLC, Wadsworth, Ohio

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Correspondence to: Olawale Oladeji, Monitoring and Research Development, Metropolitan Water Reclamation District of Greater Chicago, 6001 West Pershing Road, Cicero 60804, IL.
Email: oladejio@mwrd.org

*WEF Member/Fellow

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Abstract

The nitrogen (N) release from composted and un-composted biosolids and plant available *N* (PAN) of the biosolids were quantified to evaluate if composting can contribute to stabilize biosolids N and reduce the nitrate (NO_3^-) leaching potential in biosolids-amended soil. Biosolids were composted at >55°C for 21 days after mixing the biosolids with yard waste at 1:1 (w/w) ratio. In the N release study, we installed field lysimeters filled with soil (sand and clay) amended with composted and un-composted biosolids at two rates (30 and 150 dry Mg/ha) and measured the inorganic N in leachate after each rainfall and soil inorganic N monthly. The N released from composted biosolids during the two-year study period were lower (6% of organic N added for clay and 11% for sandy loam soil) as compared to un-composted biosolids (14% of organic N added for clay and 21% for sandy soils). Composted biosolids showed a lower N release rate constant *k* value of 0.0014 and 0.0027 month^{-1} for clay and sandy soil, respectively, compared to corresponding values of 0.0035 and 0.0068 month^{-1} for un-composted biosolids. We used greenhouse bioassay with corn (*Zea mays*), ryegrass (*Lolium perenne*), and Miscanthus (*Miscanthus giganteus*) as test plants grown for six months with reference to N chemical fertilizer ranging from 0, 75, 150 to 300 kg N/ha to evaluate the PAN of the biosolids. Based on our study, plant growth was not affected by using either composted or un-composted biosolids but the PAN was lower in composted biosolids (4.0%–5.9%) than un-composted biosolids (11.4%–13.6%). Composting results in higher N-retention efficiency in biosolids and composted biosolids are a valuable source of N to support the plant growth with lower N released to the environment. Thus, the potential of N leaching would still be low in the situations where a high rate of biosolids needs to be applied for land reclamation or landscaping soil reconstruction. © 2019 Water Environment Federation

Practitioner points

- Composting enhances N-retention efficiency in biosolids and composted biosolids are a valuable source of N to support the plant growth with lower N released to the environment.
- Potential of N leaching would still be low in the situations where a high rate of biosolids needs to be applied for land reclamation or landscaping soil reconstruction.
- N released from composted and un-composted biosolids can be adequately described by first-order kinetic model.

Key words

bioassay; lysimeters; mineralization kinetics; nitrates leaching; nitrogen mineralization; plant available nitrogen

Introduction

For the 7.2 million dry tons of biosolids generated annually in the United States (NEBRA, 2007) and millions of dry tons generated in Europe and elsewhere (Gendebien et al., 2008; Water UK, 2010), land application of biosolids as nutrient sources or soil amendment for crop/plant growth remains the best option to recycle the organic carbon (C) and nutrients in biosolids (O'Connor et al., 2005; Ronald, Peter, & Roland, 2008). The benefits of land application of biosolids are enormous

(Pierzynski, Sims, & Vance, 2005; Sharma, Sarkar, Singh, & Singh, 2017), including increased soil aeration, water-holding capacity, microbial activity, plant nutrient supply, amelioration of soil chemical properties, greenhouse gases offsetting through carbon sequestration, and reduced cost of agricultural production.

Biosolids are highly researched, but more studies are still needed to improve efficiency of its nutrients management to optimize agronomic and minimize losses to the aquatic (Al-Dhumri, Beshah, Porter, Meehan, & Wrigley, 2013; Rigby et al., 2016; Torri & Cabrera, 2017). The biosolids application at agronomic rate is based on the N requirement by the plants called N-based rate. It is expected that the agronomic N-based rate will ensure adequate N is supplied to the plants with minimal excess added N prone to leaching. Nitrogen in biosolids is dominated by organic forms (Rigby et al., 2016). As the organic N in biosolids is mineralized in soils, it releases and supplies the N needed for plant growth, thus mimicking slow-release fertilizers but with reduced N-leaching potential compared to soluble mineral fertilizers.

The utilization of biosolids may require an application rate that is more than the agronomic N-based rate, such as the situation in which biosolids products are used for land reclamation or as soil amendments for landscaping, to boost the start of plant establishment. Thus, sustainable beneficial reuse of biosolids requires management that minimizes the potential for losses of the added excess N.

Studies have indicated that treatment process can significantly affect release of biosolids N when land applied (Al-Dhumri et al., 2013; Rigby et al., 2016). Composting is an effective method to stabilize organic wastes, conserve organic N, inactivate pathogens, and recycle nutrients (Zhang & Sun, 2015). Composting stabilizes biosolids by converting part of labile forms of N into a more stable form (Amlinger, Götz, Dreher, Geszti, & Weissteiner, 2003; Doublet, Francou, Poitrenaud, & Houo, 2011), thus, reducing the mineralization of organic N in soil amendment, enhancing the retention of nutrients in soils, and reducing NO_3^- leaching of biosolids-borne N in amended soil.

An understanding of the change in N release from biosolids after composting will help to predict change in N availability from biosolids to plants and the potential of leaching when applied to land to ensure that adequate plant N is applied and the application of biosolids would not negatively impact the water quality (Burgos, Madejon, & Cabrera, 2006; Esteller, Martínez-Valdés, Garrido, & Uribe, 2009). Although some research has been conducted to quantify the N release and phytoavailability in composted biosolids (Rigby et al., 2016), information is still very limited to guide the land application of these amendments. Furthermore, since most studies on N release from biosolids are laboratory incubation with a short period (a few weeks or months), extrapolation of these data to field conditions can cause appreciable bias. Studies of N release under field conditions for more than one year are needed to evaluate potential N loss from land-applied composted biosolids at different rates and soils.

Studies have established that soil texture affects the biosolids N mineralization rate, and the N mineralization rate of biosolids depends on soil types (Rigby et al., 2016; Tester, Sikora, Taylor, & Parr, 1977). Thus, a field study was designed to measure the soil mineral N to evaluate the N release pattern of composted and un-composted biosolids at low and high application rates in sandy and clay soils under field conditions. The study was complemented with a greenhouse study to quantify and compare N recovery in plants from composted and un-composted biosolids. We hypothesized that the N release from and PAN of composted biosolids will be lower than that for un-composted biosolids.

Materials and methods

Biosolids and composted biosolids

The biosolids and composted biosolids used in the studies were produced at the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) and have a solid content of 77% and 45%, respectively. Composted biosolids were produced by mixing biosolids cake with yard waste at a mixing ratio of 1:1 (w/w) and composted according to the Federal 40 CFR Part 503 Process to Further Reduce Pathogens protocol (USEPA, 1993). The mixtures were composted at >55°C temperature in an open wind10row for 21 days. The windrows were turned after every three days for a total of five times during the active composting period and then followed by 16 weeks of curing. The un-composted biosolids used were produced by air-drying lagoon-aged biosolids. The composted biosolids were screened after curing using a 0.5-inch sieve to remove large pieces of residual feedstocks. Both composted and un-composted biosolids had concentrations of trace metals lower than pollutant limits of USEPA Part 503 (USEPA, 1993). The composted and un-composted biosolids were analyzed for selected parameters. Electrical conductivity (EC) and pH were measured using a Fisher Model 50 pH/ion/conductivity meter in 1:2 biosolids:water extraction. Total Kjeldahl nitrogen (TKN) in the amendments was analyzed by the colorimetric method following digestion with sulfuric acid in the presence of potassium sulfate and copper sulfate (USEPA, 1983). Organic carbon in biosolids was obtained by converting organic matter measured by loss-on-ignition at 375°C by a factor of 1.724.

Field lysimeter study on N release from biosolids

The field incubation study was conducted for two years (Year 1, April – December and Year 2, January – December) at a research site of the MWRDGC located at Cicero, Illinois. The total rainfall at the site during the study was 1,121 and 1,168 mm in Year 1 and Year 2, respectively. The mean annual temperature during the study was 8.6 and 10.1°C in Year 1 and Year 2, respectively, and both rainfall and temperature peaked between June and August during the two study years. Before the study, the field was a grassy area. The holes were dug to the depth of 25 cm each to install incubation lysimeters containing treatments. Two soils of different textures used in the field study, sandy loam (sand = 70%, silt = 20%, clay = 10%) and clay (sand = 30%, silt = 20%, clay = 50%)

Table 1. Selected properties of composted and un-composted biosolids and soils used for the field lysimeter study

	SOLIDS	PH	EC	NH_4^+- *N*	NO_3^--*N*	TKN	ORGANIC C	C:*N*
	%		MS/CM	MG/KG	MG/KG	MG/KG	%	RATIO
Amendment								
Un-composted biosolids	77	6.5	4.6	637	552	28,134	21	7.5
Composted biosolids	45	6.8	2.4	29	411	24,855	22	8.9
Soil								
Sandy Loam	–	6.1	0.1	16.7	11.7	1,304	1.7	–
Clay	–	6.3	0.2	15.9	7.0	1,308	1.4	–

Table 2. Summary table of the two (lysimeter and greenhouse) studies

ITEM	LYSIMETER STUDY	GREENHOUSE STUDY
Type of study	Field	Greenhouse
treatments	Five treatments: 1. Composted biosolids applied at 30 Mg biosolids/ha 2. Composted biosolids applied at 150 Mg biosolids/ha 3. Un-composted biosolids applied at 30 Mg biosolids/ha 4. Un-composted biosolids applied at 150 Mg biosolids/ha 5. Control (no amendment)	Six treatments: 1. Composted biosolids at the rate equivalent to 870 kg N/ha 2. Un-composted biosolids at the rate equivalent to 870 kg N/ha 3. Control soil at 0 kg N/ha 4. Control soil with chemical fertilizer at 75 kg N/ha 5. Control soil with chemical fertilizer at 150 kg N/ha 6. Control soil with chemical fertilizer at 300 kg N/ha
Soil type tested	Two soils (clay and sandy loam)	One soil (sandy loam)
Design	Randomized complete block	Randomized complete block
Plant grown	None	Corn, Ryegrass, and Miscanthus
Duration	2 years	6 months
Nitrogen form estimated	N release	Plant available N (PAN)

soils, were obtained from farmlands at Matteson, Illinois. Soil organic carbon was measured by Walkley-Black wet oxidation (Nelson & Sommers, 1996). Soil pH, EC, and TKN were measured using the same methods as for biosolids. Soil NO_3^--N and NH_4^+-N were measured by extracting the soil with 2N KCl and the extract analyzed using a Lachat Quickchem flow injector autoanalyzer (Zellweger Analytics). The two soils had similar pH, TKN, and ammonium nitrogen (NH_4^+-N) with greater nitrate nitrogen (NO_3^--N) in sandy loam than clay soil (Table 1).

Each of the two soil types was weighed (12 kg per experimental unit) and mixed with either of the two amendments (composted biosolids and un-composted biosolids) at either of the two rates (30 and 150 Mg biosolids/ha). The 30 Mg/ha application rate is equivalent to the biosolids agronomic N-based rate, while the 150 Mg/ha, which is five times the agronomic rate, was included to mimic cases such as the typical high rates often used when biosolids are utilized as a soil amendment such as for landscape construction and land reclamation.

The soils and amendments for each treatment were weighed and thoroughly mixed using a mixer. A control soil without an amendment was included for each soil type and all treatments replicated three times. The experimental units were 30-cm high lysimeters designed with two compartments. The upper compartment was 20-cm deep. The soil was packed in the upper compartment to a depth of 15 cm, leaving 5 cm above the surface of soils to prevent surface runoff and cross contamination between the experimental units during rain events. The lower compartment (10 cm) was left empty for collection of leachate following each rain event. The 30 lysimeters (2 amendments × 2 application rates × 2 soils and a control of each soil with no amendment and replicated three times) were buried in the field to a depth of 25 cm in a randomized complete block design (Table 2).

Leachates collected after each rain event were pumped out of the lower compartment to measure the volume, and a sub-sample was used for analysis of NO_3^--N and NH_4^+-N using a Lachat Quickchem flow injector autoanalyzer (Zellweger Analytics). The mass of N in leachate after each rain event was calculated as the product of NO_3^--N and NH_4^+-N concentrations and volumes, and the monthly N amount in the leachate was determined as the sum of leachate N mass of all rain events during the month.

In addition to the N released to the leachates, monthly soil samples were taken from each treatment and analyzed for NH_4^+-N and NO_3^--N by extracting with a 2M KCl (Mulvaney, 1996), and the extracts analyzed using a Lachat Quickchem flow injector autoanalyzer (Zellweger Analytics).

Greenhouse study for measuring biosolids PAN

The biosolids PAN was quantified using corn (*Zea mays*), ryegrass (*Lolium perenne*), and Miscanthus (*Miscanthus* *giganteus*) as test plants grown separately in soil amended with the composted or un-composted biosolids for 6 months in a greenhouse (Table 2). The three test plant species were selected to represent typical crops fertilized with biosolids. The study with four replicates had six treatments arranged in randomized complete block design. Two of the treatments are un-composted and composted biosolids applied to provide 400 mg total N/kg soil (equivalent to 870 kg total N/ha) each. The other four treatments were the control, which received no compost or biosolids amendment but ammonium nitrate fertilizer at 0, 35, 69, and 138 mg N/kg (equivalent to 0, 75, 150, and 300 kg N/ha, respectively). The chemical fertilizer treatments were included in the study as a standard to evaluate the equivalent rates of biosolids to N immediately available fertilizer for obtaining PAN. The composted and un-composted biosolids applied at total N rate (870 kg total N/ha) that was four to five times the typical N rate for turf (~180 kg N/ha) and corn (~220 kg N/ha), taking into account that possibly less than 25 percent of the total N in these materials is plant available (Sharma et al., 2017).

Composted biosolids, un-composted biosolids, and fertilizer needed for each treatment were weighed and blended with 3 kg of topsoil (sandy loam) collected from Brookemere, Matteson, Illinois. All pots treated with chemical fertilizer also received Sul-Po-Mag to provide sufficient sulfur, potassium, and magnesium. The amended soils were placed in 8-inch depth pots, and water was added as needed to the soil (in the pots) to field capacity. The initial weight of the pots at field capacity was measured and water added (depending on the weight loss of the pots) to maintain the soil moisture near field capacity during the study. Drainage was collected in saucers placed underneath each pot and was poured back into the respective pots.

Corn was grown three times in succession for biomass (June 1 to July 13, July 13 to August 29, and September 4 to November 26). At the end of each corn cropping, the aboveground biomass was harvested and dried. Corn roots were removed, thoroughly washed with deionized water, dried, and weighed. The ryegrass was clipped monthly, dried, and weighed. Miscanthus was harvested twice (August and November 2013) and aboveground dry biomass yield was measured. The dried plant tissue samples were ground in a Willey mill using a 2-mm screened. All plant samples were analyzed for N following acid digestion method.

Data processing and calculation of N release rate of biosolids

The monthly N released in each treatment can be estimated using the change in sum of leachate inorganic N and soil inorganic N relative to soil inorganic N in the previous month as follows:

$$\mathrm{NR}_t = \mathrm{IN}_{(\mathrm{leachate})t} + \mathrm{IN}_{(\mathrm{soil})t} - \mathrm{IN}_{(\mathrm{soil})t-1},$$

where NR_t = N released from amended soil or control soil during month "t"; IN = inorganic *N* (NO_3-N + NH_4-N); $\mathrm{IN}_{(\mathrm{leachatet})}$ = total inorganic N in leachates during the month "t"; $\mathrm{IN}_{(\mathrm{soil})t}$ = inorganic N in soil at month "t".

The N released from composted biosolids or un-composted biosolids could be calculated as the difference in N released (NR_t) between amended soil and the control.

Thus, the remaining of organic N from added biosolids at time t (ON_t) could be obtained as:

$$\mathrm{ON}_t = \mathrm{ON}_{0(\mathrm{amendment})} - \text{cumulative } \mathrm{NR}_{(\mathrm{amendment})t},$$

where ON_0 = organic N added from biosolids and $\mathrm{NR}_{(\mathrm{amendment})t}$ = N released from composted biosolids or un-composted biosolids

It is known that the depletion of ON_0 is a function of rate k and time t:

$$\mathrm{dN}/\mathrm{d}t = k\mathrm{ON}.$$

On integration the equation yields an exponential function:

$$\mathrm{ON}_t = \mathrm{ON}_0 e^{k_t}.$$

Thus, the N release rate constant (k) was obtained as the slope after plotting linearized equation of natural log of ON_t versus t from above equation.

Calculation of biosolids plant available N

Plants N uptake. Plant N uptake was calculated as a product of dry matter yield and plant tissue N concentration. The biosolids-derived plant N uptake was calculated as the difference in total plant N uptake between biosolids treatment and control (0 kg N/ha).

Plant Available N (PAN). The amount of PAN in composted and un-composted biosolids was calculated as the biosolids-derived plant N uptake divided by the mean of increases in plant N uptake per unit fertilizer N over the three-rate intervals: 0–75 kg, 75–150 kg, and 150–300 kg N/ha, as proposed in Tian, Kolawole, Kang, and Kirchhof (2000). Thus, the biosolids PAN in percentage can be calculated as biosolids PAN amount divided by total N applied via biosolids and multiplied by 100.

Statistical analysis

The assumption of normality was verified by the Kolmogorov–Smirnov method for all the datasets (Drezner, Turel, & Zerom, 2010). The nonlinear procedure (Proc Nlin) of SAS (Littell, Milliken, Stroup, & Wolfinger, 1996) was used to obtain the best fit to obtain the N release rate constant, k, for composted and un-composted biosolids applied to each of the two soils tested. The N released and greenhouse data were analyzed by the conventional analysis of variance approach (ANOVA) using SAS (Littell et al., 1996). The treatments were compared by Turkey's test using SAS software (SAS Institute, 1995). Statistical differences were declared at significance (α) level of .05.

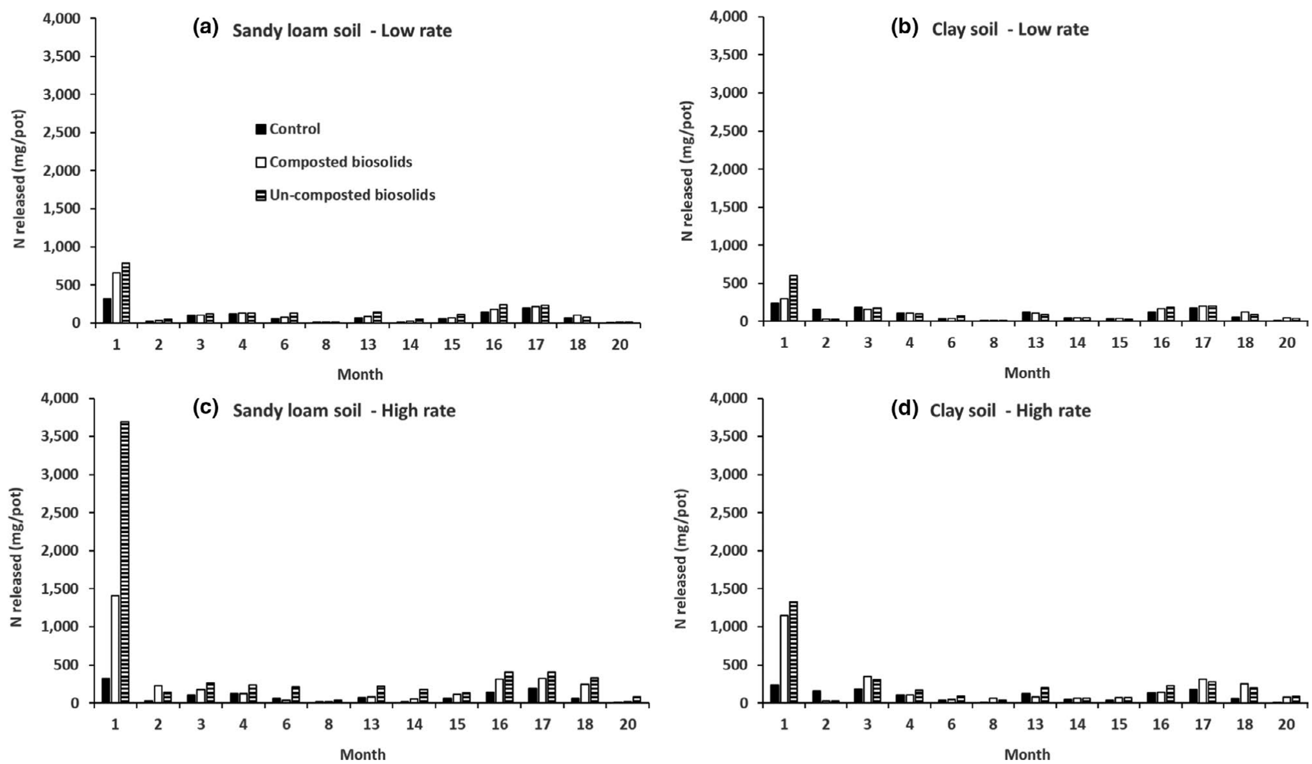

Figure 1. Total monthly inorganic N released in un-amended soils (controls) and soils amended with composted and un-composted biosolids at low-rate equivalent to 30 Mg/ha (a and b) and high-rate equivalent to 150 Mg/ha (c and d) during the two-year lysimeter study.

Results

Characteristics of biosolids and soil

Selected chemical properties of the two amendments used in the study are shown in Table 1. Organic carbon content of the composted biosolids was 22%, similar to that in the un-composted biosolids used (21%), but the TKN in the composted biosolids was 2.5%, slightly lower than in un-composted biosolids (2.8%). Thus, the C:N ratio in the composted biosolids (8.9) was slightly greater than in un-composted biosolids (7.5). The inorganic *N* (NO_3^--N and NH_4^+-N) were lower in composted biosolids (NO_3^--*N* = 411 mg/kg; NH_4^+-*N* = 29 mg/kg) than in un-composted biosolids (NO_3^--*N* = 552 mg/kg; NH_4^+-*N* = 637 mg/kg). Though the pH of the composted and un-composted biosolids was similar, composting reduced the EC in biosolids with 2.4 mS/cm in composted biosolids and 4.6 mS/cm in un-composted biosolids.

Nitrogen release rate difference between composted and un-composted biosolids

The N release in amended and un-amended soils was estimated as the change in the monthly sum of inorganic N measured in both leachates and soils (Figure 1). Trends of N-released data indicate the impacts of composting, application rate, and soil type on N released. In sandy loam soil, more than half of the N released occurred within the first two months of the study. The N release in clay soils was relatively slow. Generally, at the end of the two-year study period, the cumulative N released in the un-amended control soils was similar in sandy loam (1,216 mg/pot^{-1}) to that in clay soils (1,320 mg/pot). Greater N release was observed in amended sandy loam soil than in amended clay soil at both high and low application rates (Figure 1). N release was greater in soils treated with un-composted biosolids than in those treated with composted biosolids, particularly with high application rate in sandy loam soil and low application rate in clay soil. At the end of the two-year study, the cumulative N released in the sandy loamy soil treated with un-composted biosolids (2,114 mg/pot for low rate and 6,330 mg/pot for high rate) was more than that released in the same soil treated with composted biosolids (1,714 mg/pot for low rate and 3,153 mg/pot for high rate) based on the data in Figure 1. A similar trend was observed in clay soils where the cumulative N released in soils with un-composted biosolids (1,690 mg/pot for low rate and 3,093 mg/pot for high rate) was more than that released in soils treated with composted biosolids (1,392 mg/pot for low rate and 2,729 mg/pot for high rate).

The net N released from added amendments (composted and un-composted biosolids) was obtained by accounting for N release from background soil (control). The N released was affected by amendment, soil types, and application rates. The N released from the amendments was greater in the first than second year at each of the two application rates. For the study period, un-composted biosolids released more N than composted biosolids at each of the application rates, except during the second year where similar N was released by both amendments from clay soil treated with low rates of the amendments. The percentage of organic N released was lower from

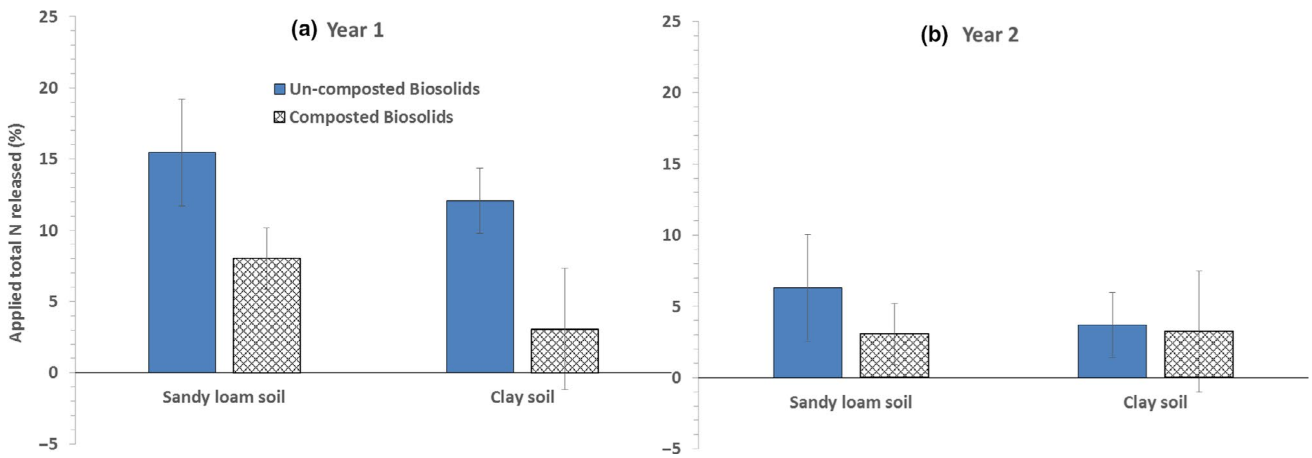

Figure 2. Percentage of applied organic N released from the composted and un-composted biosolids applied to sandy loam and clay soil during (a) Year 1 and (b) Year 2 of the lysimeter study. Mean of low and high rates of biosolids. Error bars denotes one standard deviation.

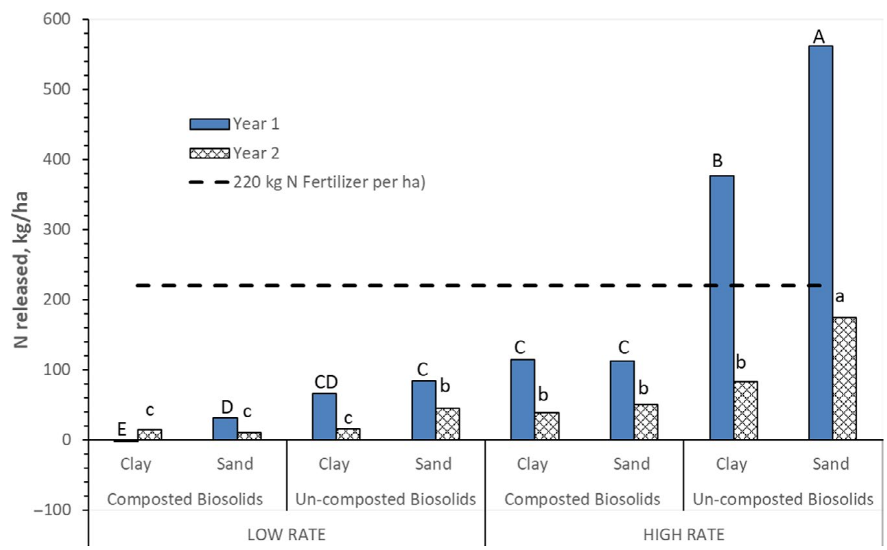

Figure 3. Total N released from composted and un-composted biosolids applied at low (30 Mg/ha) and high (150 Mg/ha) rate to sandy and clay soil during first and second year of the lysimeter study. Bars of Year 1 with the same uppercase letter (A, B, C, or D) are not significantly different at the $p = .05$ value. Bars of Year 2 with the same lowercase letter (a, b, or c) are not significantly different at the $p = .05$ value.

composted biosolids than un-composted biosolids in both years (Figure 2), and it was greater for the first year than the second year for both amendments. During the two-year study period, the percentage of organic N released was 6% for clay and 11% for sandy soil from composted biosolids as compared to 14% for clay and 21% for sandy soil from un-composted biosolids.

Even at a high rate, the annual N released from composted biosolids was lower than the typical 220 kg N/ha agronomic N rate applied as chemical fertilizer (Figure 3). Though the high rate of amendments used in this study was five times more than the agronomic rate (low rate), the N released from applied composted biosolids at a high rate was still comparable to or lower than N released from applied un-composted biosolids at an agronomic rate for both soils (Figure 3).

The potential N release from both composted and un-composted biosolids was adequately described by the first order kinetic model which provided the N release rate constant (k). Composted biosolids showed significantly lower k values of 0.0014 and 0.0027 month^{-1} for clay and sandy soil, respectively, compared to corresponding values of 0.0035 and 0.0068 month^{-1} for un-composted biosolids (Table 3).

Plant available N (PAN) difference between composted and un-composted biosolids

In general, dry matter yields of corn, ryegrass, and Miscanthus increased with the increasing rate of chemical fertilizer, and the highest dry matter yields were observed at 150 kg N/ha and 300 kg N/ha fertilizer treatment. The yield at 150 kg N/ha fertilizer treatment was similar to that at 300 kg N/ha. The DM yields of corn and ryegrass were, in most cases, greater in the composted and un-composted biosolids treatments than in the control treatment that received 0 kg N/ha. The DM yields of

Table 3. Nitrogen released rate constant of the composted and un-composted biosolids applied to sandy loam and clay soil of the lysimeter study

AMENDMENT	SANDY LOAM SOIL	CLAY SOIL
	K (MONTH^{-1})	
Un-composted biosolids	6.8×10^{-3} a	3.5×10^{-3} a
Composted biosolids	2.7×10^{-3} b	1.4×10^{-3} b

Values within the same column followed by the same letter (a, b) are not significantly different at the 0.05 level of probability.

most crops planted in the un-composted and composted biosolids treatments were not significantly different from the optimum yield observed in the treatment that received 150 kg N/ha chemical fertilizer (Table 4). Dry matter (DM) yields of corn, ryegrass, and Miscanthus grown in pots were not significantly different between composted and un-composted biosolids treatments. However, the values tended to be lower with composted than un-composted (Table 4).

Plant tissue N concentrations (data not shown) increased with an increasing rate of fertilizer application. Composting had a minimal impact on the effect of biosolids application on ryegrass and Miscanthus N concentrations, but higher plant tissue N concentrations were observed in corn grown in pots amended with un-composted biosolids than composted biosolids.

The N uptake by corn and ryegrass increased with increasing rate of chemical fertilizer (Table 4). Again, the differences in the N uptake by corn, ryegrass, and Miscanthus between composted biosolids and un-composted biosolids were not significant, but the values tended to be lower with composted than un-composted. The portions of the applied total N taken up by the plants were greater in un-composted biosolids (6%–10%) than in the composted biosolids (<5%) (Table 4). Similarly, the PAN of the composted biosolids (4.0%–5.9%) was lower than that of the un-composted biosolids (11.4%–13.6%) (Figure 4).

Discussions

The slightly lower TKN of the composted biosolids applied (2.4%) than in un-composted biosolids (2.8%) (Table 1) could result from a combination of dilution of biosolids N by added yard wastes and loss of N as NH_3 during composting. The total N in the two residuals falls within the values reported in biosolids (Rigby et al., 2016; Sommers, 1977). The mineral inorganic *N* (including NO_3^--N and NH_4^+-N) in the composted biosolids was also lower than that in the un-composted biosolids. Biosolids N is mostly in organic form, which requires mineralization to release N for plant use. At an agronomic rate, biosolids are expected to release N needed for plant growth with minimal N leaching. Other studies also reported lower inorganic N in composted biosolids than in un-composted biosolids (Kokkora, 2008; Zwart, 2003). Parker and Sommers (1983) reported lower mineral inorganic N (4.2% of total N) in composted biosolids than observed in un-composted air-dried biosolids (>5% of total N). Observed lower inorganic N

Table 4. Total dry matter yield, N uptake, and percentage of applied N taken up by plants (corn, ryegrass, and Miscanthus) during the greenhouse study

TREATMENTS	DRY MATTER (G/POT)			N UPTAKE (MG/POT)			APPLIED N TAKEN UP BY PLANTS (%)		
	CORN	RYEGRASS	MISCANTHUS	CORN	RYEGRASS	MISCANTHUS	CORN	RYEGRASS	MISCANTHUS
Un-composted biosolids	26.4 ab[b]	6.0 a	10.3 a	268 b	162 ab	110 b	8.1	6.4	6.0
Composted biosolids[a]	22.1 bc	5.4 ab	8.7 b	184 c	113 b	92 bc	1.1	3.9	4.5
Fertilizer @ 0 kg *N*/ha	21.0 c	3.6 c	8.6 b	171 c	81 c	79 c	NA[c]	NA	NA
Fertilizer @ 75 kg *N*/ha	21.9 c	5.2 ab	9.0 ab	212 c	106 b	90 bc	39.7	24.5	11.1
Fertilizer @ 150 kg *N*/ha	26.2 ab	6.1 a	12.0 a	265 b	154 ab	115 ab	45.6	46.1	17.6
Fertilizer @ 300 kg *N*/ha	30.0 a	6.8 a	11.4 a	418 a	220 a	135 a	59.8	32.2	13.6

[a]All composts are generated from 1:1 ratio of biosolids:landscape waste.
[b]Means within a column followed by the same letter (a, b, or c) are not significantly different at .05 probability.
[c]Not applicable.

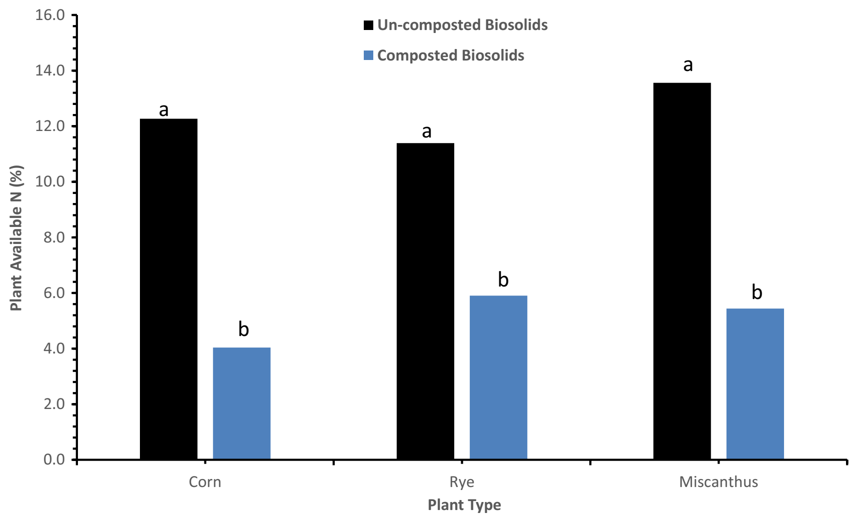

Figure 4. Plant available N of composted and un-composted biosolids for the three plants tested during the greenhouse study (columns of the same plant followed by different letter (a or b) are significantly different at 0.05 probability).

of composted than un-composted biosolids could results from N loss by volatilization of ammonia and immobilization due to microbial activities during composting.

The C:N ratio of the composted biosolids (7.5) and un-composted biosolids (8.9) is <12. Iglesias-Jimenez and Alvarez (1993) indicated that C:N ratio <12 will result in net N mineralization when organic soil amendment is land applied. Gutser, Ebertseder, Weber, Schraml, and Schmidhalter (2005) also indicated that organic amendments with C:N less than 15 can show N release and provide available N to plants. Thus, net immobilization was not expected in the tested composted and un-composted biosolids, but reduced N mobility or leaching is expected when land application of biosolids processed through composting. During composting, the labile organic compounds, including N-containing proteins, are rapidly transformed into more stable forms with a reduced potential for mineralization. Other studies also suggest that the increase in cation exchange capacity (CEC) of composted materials, coupled with stability increase, is expected to improve nutrient retention in soils (Preusch, Adler, Sikora, & Tworkoski, 2002).

Nitrogen release and composting

The greater N released from un-composted biosolids than composted biosolids applied observed in this study is consistent with findings in other studies that show that composting stabilizes and reduces potential nutrient losses (Dere, Stehouwer, Aboukila, & McDonald, 2012). Mineralizable N of 15% and 8% was reported by Parker and Sommers (1983) for anaerobically digested and composted biosolids, respectively. In a recent review, Rigby et al. (2016) indicated that the differences in the N availability coefficient (NAC) of biosolids depended on the process used for stabilization and suggested mean NAC of 0.47, 0.40, 0.34, 0.30, and 0.07 for aerobically digested biosolids, thermally dried biosolids, lime-treated biosolids, mesophilic anaerobic digestion biosolids, and composted biosolids, respectively. Thus, highly stabilized biosolids, such as composted biosolids, should ensure that utilization of a high-rate amendment will not cause a concern for N leaching. In recognition of the differences expected from composted and un-composted biosolids, the USEPA included mineralization factors of 10% (for composted biosolids), 20% (for anaerobically digested biosolids), and 30% (for aerobically digested biosolids) for the land application (USEPA, 1995).

In this study, the soil type and application rates also affected the N released from biosolids. Un-composted biosolids applied at a high rate to sandy soil had the greatest N release during the study period, and composted biosolids applied at a low rate to clay soil had the least N release (Figure 2). Nitrogen release from land-applied biosolids reported in literature is highly variable (Chae & Tabatabai, 1986; Wang, Kimberley, & Schlegelmilch, 2003). The N released from the biosolids in this study (14%) is similar to the 13% mineralization rate reported by Kumar, Hundal, Cox, and Granato (2014) for the air-dried biosolids from the same source. Factors reported to affect N release include biosolids processing, soil, and climatic factors. Dewatering, lagoon storage, and air-drying are examples of processing factors that can reduce N release. Gilmour, Cogger, Jacobs, Evanylo, and Sullivan (2003) ascribed low mineralizable N values to a long drying period and loss of ammonia. Tester et al. (1977) reported 0%–6% net N mineralization from organic N in composted biosolids and showed higher N release from loamy sand than a silty clay loam or a silty loam. Smith, Woods, and Evans (1998) reported 7%–25% of organic N mineralized following 73 days of incubation at 25°C.

More than half of the N in biosolids and other organic soil amendments are tied up in organic fragments (Pierzynski & Gehl, 2005; Pierzynski et al., 2005) that have to be mineralized to release the nutrients. The study shows N released from composted biosolids at a high rate was below the typical 220 kg N/ha agronomic N rate often applied as chemical fertilizer. The lower N released from compost suggests that even when applied at high rates, it is not expected to pose as much risk as in the agronomic rate of chemical fertilizer to the environment. The findings are consistent with other studies (Binder, Dobermann, Sander, & Cassman, 2002; Brenton, Fish, & Mata-Gonzalez, 2007; Rajendram, Surapaneni, & Smith, 2011) and established that composting reduces the environmental impact of higher rates of biosolids application and mitigates excessive N release from amended soils.

The N release of both the biosolids and composts show a decreased rate in the second year compared to the first year of study. A similar pattern was observed in other studies (Chae & Tabatabai, 1986; Sims & Stehouwer, 2008). The trend is also consistent with studies that indicated that biosolids have two organic matter fractions, readily mineralizable and refractory (Tian et al., 2009; Torri, Studart Corrêa, & Renella, 2014). The lower N release rate constant (k) of composted biosolids than un-composted biosolids found in this study confirms that the N release rate was affected by the composting status of the amendment. Our study also confirmed the interaction of N release from biosolids with soil texture. Sandy soil show greater N release than clay soils and this is consistent with greater N mineralization rate reported in clay than in sandy soils by Hall (1983) and Hernández et al. (2002), which can be attributed to higher aeration in sandy than in clay textured soils. Clay also protects organic particles from microbial attack than in sandy soils. However, there could be exceptions for greater mineralization and nitrification rates reported in clay than sandy soils due to the presence of highly active microbial populations containing organic matter (Correa, White, & Weatherley, 2006; Rigby, Perez-Viana, Cass, Rogers, & Smith, 2009).

Similar DM yields of corn, ryegrass, and Miscanthus with both composted and un-composted biosolids indicates minimal impact of composting on biosolids to support crop growth (Table 4). Both composted and un-composted biosolids enhance crop growth and are consistent with other studies that documented increased DM yield with compost application (Clark, Stanley, & Maynard, 2000; Iglesias-Jimenez & Alvarez, 1993). This study suggests that the 150 kg N/ha fertilizer application rate supplied an optimum amount of nutrients to meet corn needs, and there was no additional response to N at the 300 kg N/ha rate. The similar DM yields of most crops planted in the un-composted and composted biosolids treatments to the optimum yield observed in the 150 kg N/ha chemical fertilizer treatment established that composted biosolids supplied sufficient N to support and meet the requirements of corn, Miscanthus, and rye grass. Phytoavailable N was lower in composted than in un-composted biosolids treatments and consistent with studies that reported lower compost N recovery in plants (Alvarez-Campos & Evanylo, 2019; Amlinger et al., 2003; Hartl & Erhart, 2005; Wolkowski, 2003). The estimated N recovery in un-composted biosolids was greater than in the composted biosolids. Thus, a higher rate of composted biosolids will be required to supply similar PAN as in un-composted biosolids.

Conclusions

Inorganic N released from composted biosolids during this two-year study period were lower (6% for clay and 11% for sandy soil) as compared to un-composted biosolids (14% for clay and 21% for sandy soils). This study also shows that N released from applied biosolids at five times the agronomic rate was reduced to the level obtained at the agronomic rate when applied as composted biosolids. The use of composted biosolids can reduce the N release potential from biosolids in situations that require biosolids application at high rates such as soil amendment to establish vegetation and restoration of degraded ecosystem. The potential N released from both composted and un-composted biosolids was adequately described by the first-order kinetic model, which gave a lower N release rate constant (k) for composted biosolids (k values of 0.0014 and 0.0027 month^{-1} for clay and sandy soil, respectively) compared to un-composted biosolids (k values of 0.0035 and 0.0068 month^{-1} for clay and sandy soil, respectively). The study showed that application of composted biosolids resulted in greater biosolids N-retention efficiency in both soils, enhancing the amendment's environmental benefits. The reduction in N released by composting affected phytoavailable N and limit luxury N uptake by plants but did not reduce plant growth.

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