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Application of municipal solid waste (MSW) to arable land can be used to close the nutrient cycle between urban and rural areas. The aim of the current study was to quantify net N mineralization and respiration from composted MSW (CMSW) and anaerobically digested MSW (ADMSW) applied to soil, and to test whether a simple relationship between net N mineralization and respiration that was developed for plant materials, was applicable for these types of MSW. In a laboratory experiment, CMSW and ADMSW were incorporated into soil and incubated at 15°C. During the 149-day experiment, net N mineralization and respiration were determined. Cumulative respiration derived from both MSW types was very steep during the first 30 days, after which it levelled off. However, calculated on the basis of applied C, the ADMSW was 10 times more degradable than the CMSW. Both MSW types caused initial net N immobilization followed by re-mineralization. A simple model based on the relationship between net N mineralization and respiration was only applicable for the MSW after significant modifications. If farmers are to recognize CMSW and ADMSW as valuable fertilizers, it is important that they can be produced with higher maturity, in order to avoid initial N immobilization.

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Introduction

Municipal solid waste (MSW) is largely incinerated or landfilled in many parts of the world. However, in recent years there has been an increasing awareness of alternative waste management methods. For instance, after source separation into organic and inorganic fractions, organic MSW can be either composted or anaerobically digested, with the accompanying methane production to be used as an energy source (Barth & Kroeger 1998, Goldstein 2003, Evans 2004). Application of composted (CMSW) or anaerobically digested MSW (ADMSW) to arable land can be used to close the nutrient cycle between urban and rural areas. For organically managed soils in peri-urban areas (Magid *et al.* 2006b) and low input systems in metropolitan areas of less developed countries (Refsgaard *et al.* 2006) in particular, inputs of MSW could help to balance nutrient exports with imports. However, only relatively few studies have been published on how CMSW affects soil fertility and nutrient dynamics (Bernal *et al.* 1998, Niklasch & Joergensen 2001, Hartl *et al.* 2003, Pansu & Thuriès 2003) and even fewer on the effects of ADMSW (Bruun *et al.* 2006a).

Net nitrogen (N) mineralization in soil is the outcome of two concurrent and opposing processes: gross N mineralization and gross N immobilization (Murphy *et al.* 2003, Luxhøi *et al.* 2005). Gross N immobilization rate has been found correlated to respiration rate for several soils (Hart *et al.* 1994, Recous *et al.* 1999, Barrett & Burke 2000, Bengtsson *et al.* 2003, Luxhøi *et al.* 2006). However, gross N mineralization rate is only correlated to respiration rate for soils with relatively narrow C/N ratios (Hart *et al.* 1994, Bengtsson *et al.* 2003). Following soil amendment with crop residues possessing a very wide range of C/N ratios, Luxhøi *et al.* (2006) found no significant correlation between gross N mineralization and respiration rate. Only by taking the C/N ratio of the decomposing pool into account can a correlation be expected (Murphy *et al.* 2003, Saetre & Stark 2005, Luxhøi *et al.* 2006). Based on these relationships for gross N mineralization and immobilization, Bruun *et al.* (2006b) developed a net N mineralization model, which they validated against a C and N mineralization data set (Jensen *et al.* 2005) consisting of incubation data from 76 different plant materials.

The aim of the current study was to quantify net N mineralization and respiration from composted and anaerobically digested MSW applied to soil, and to test whether the simple relationship between net N mineralization and respiration is applicable for these organic materials.

Materials and methods

Soil and treated MSW

The soil used in the experiment was collected from the top 20 cm of an organically managed arable field at the experimental station of the Faculty of Life Science, Copenhagen University (12°E, 56°N; 30 m a.s.l.). The soil is a sandy loam that at sampling contained 1.23% C and 0.12% N, and had a pH of 7.0 (0.01 mol/L $CaCl_2$). The soil was adjusted to a water content of 17% (w/w), and was pre-incubated for 3 weeks at 15°C. Two types of treated MSW were used in the experiment: (1) ADMSW, made from a mix of woodbark chips, mesophilic decomposed sewage sludge and organic kitchen waste (1 : 1 : 2, w : w), was produced by the private company Solum Ltd. (Hedehusene, Denmark) in a 2.5 m^3 container and was digested over a 2-month period; and (2) CMSW, made by the renovation department of Vejle County (Vejle, Denmark) from 60% municipal sorted waste and 40% garden waste (shredded to 10 mm) and composted over a 4-month period. Additional information on the composition is given in Table 1. The treated MSWs were chopped into pieces of maximum dimension 5 mm. In large containers (10 L) they were incorporated as homogeneously as possible into the pre-incubated soil. ADMSW was applied at a rate of 1.6% (dry weight basis), and CMSW was applied at a rate of 6.4% (dry weight basis). These amounts corresponded to somewhat similar N release rates based on preliminary studies. Soil without MSW incorporation served as a control. From each of the three soil containers, 50 g of soil (dry weight basis) were weighed into each of 15 incubation vessels, making a total of 45 vessels with 50 g of soil in each. The soils were compressed to a bulk density of 1.2 g cm^{-3} (dry weight basis) and transferred to a 15°C incubator.

Table 1: Characteristics and application with treated composted (C) and anaerobically digested (AD) MSW.

Parameter	Unit	CMSW	ADMSW
Application rate	% wet weight	21	2.5
Dry matter	%	31	63
Mineral N	% dry weight	0.09	0.47
	mg kg^{-1} soil (dry mass)	54	72
Organic N	% dry weight	1.5	2.1
	mg kg^{-1} soil (dry mass)	945	333
Organic C	% dry weight	42	27
	mg kg^{-1} soil (dry mass)	27036	4358
$C/N_{organic}$		29	13
Conductivity	10 mS cm^{-1}	7.6	
pH		8.0	

Three incubation vessels from each treatment were randomly selected and placed in separate sealed 1 L glass jars together with water and a vial containing 0.1 mol/L NaOH solution. At regular intervals during the incubation, the NaOH vials were removed for determination of CO_2 evolution by HCl titration, and fresh NaOH vials were placed in the glass jars. Each time the NaOH vials were changed, the incubation vessels were also changed, in order to obtain time-independent measurements. Microbial respiration was calculated as the difference in CO_2 evolution between treatments and blanks. Mineral-N ($NH_4^+ + NO_3^-$) was determined by extracting 20 g of soil (dry weight basis) from each of three vessels from each treatment in 80 mL 1 mol/L KCl for 45 min in an end-over-end shaker, and filtering through Advantec filter paper no. 5C. Ammonium-N and nitrate-N in the soil extracts were determined by a flow injection analyser system (Lachat Instruments Division). Ammonium-N was determined by the gas diffusion method, and nitrate-N was determined by the cadmium reduction method. Net N

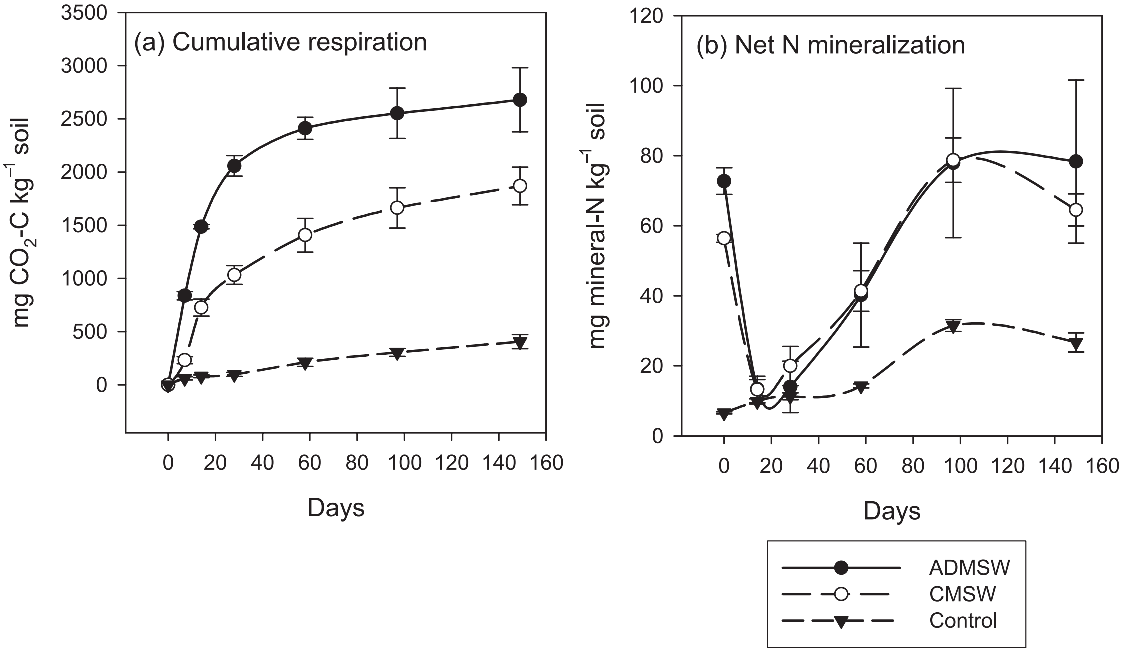

Fig. 1: Measured respiration and net N mineralization pattern of soil (control) and soil with incorporated composted MSW or anaerobically digested MSW. Error bars represent standard errors.

mineralization was calculated as the difference in pool size of inorganic N between treatments and control. Total C and N in the pre-incubated soil were determined on a mass spectrometer (20–20) coupled to an ANCA-SL sample preparation module (both Europe Scientific, Crewe, UK). The total C in the MSW samples was also determined on the mass spectrometer, and the total N was determined by the Kjeldahl digestion method (Kjeldahl 1883) in order to include ammonium-N.

Modelling

Cumulative C respiration derived from the MSW types ($C(t)_{MSW}$) was calculated as the difference between treatments and control, and expressed on the basis of g respired C g^{-1} added C. Likewise, net N mineralization derived from the MSW ($N(t)_{MSW}$) was calculated as the difference between treatments and control, and expressed on the basis of g mineralized N g^{-1} added C. $C(t)_{MSW}$ was fitted to a three-pool model (1) using the solver function in Excel®, where $C_{MSW\text{-}f1}$ represents the labile MSW fraction and $C_{MSW\text{-}f2}$ represents the recalcitrant MSW fraction with the corresponding decay rates $k_{MSW\text{-}f1}$ and $k_{MSW\text{-}f2}$. The remaining inert MSW fraction ($1 - C_{MSW\text{-}f1} - C_{MSW\text{-}f2}$) was assumed not to be degraded within the timeframe of the experiment.

$$C(t)_{MSW} = C_{MSW-f1}\cdot\left(1-e^{-k_{MSW-f1}\cdot t}\right) + C_{MSW-f2}\cdot\left(1-e^{-k_{MSW-f2}\cdot t}\right) \qquad (1)$$

According to Bruun *et al.* (2006b), net N mineralization from decomposing plant residues can be predicted from the residue-derived CO$_2$ respiration from equation (2), where C/N is the C/N-ratio of the decomposing plant residue, and a_1, a_2 and B are constants. Equation (2) was used as a model to describe the net N mineralization from the MSW.

$$N(t)_{MSW} = \left(\frac{a_1}{C/N} - a_2\right)\cdot C(t)_{MSW} + B\cdot t \qquad (2)$$

Results and discussion

In the following section, the use of models is not intended to be predictive. They are rather used (cf. Magid *et al.* 1997, 2006a) in an exploratory interpretation of data which do not conform to well-described organic residues (Jensen *et al.* 2005).

Cumulative respiration

Composted MSW

After a short lag phase, the soil with added CMSW showed a steep increase in the cumulative respiration in the first 30 days, after which it gradually levelled off (Figure 1a). Calculated on the basis of applied C, only 5% of the applied CMWS-C was respired during the 150-day incubation (Figure 2). This reflects the fact that compost has already decomposed for a long time and the remaining material is resistant to degradation (Pansu & Thuriès 2003). The fit of the accumulated respiration from CMSW using equation (1) (see Figure 2) resulted in a labile pool of 4%, a recalcitrant pool

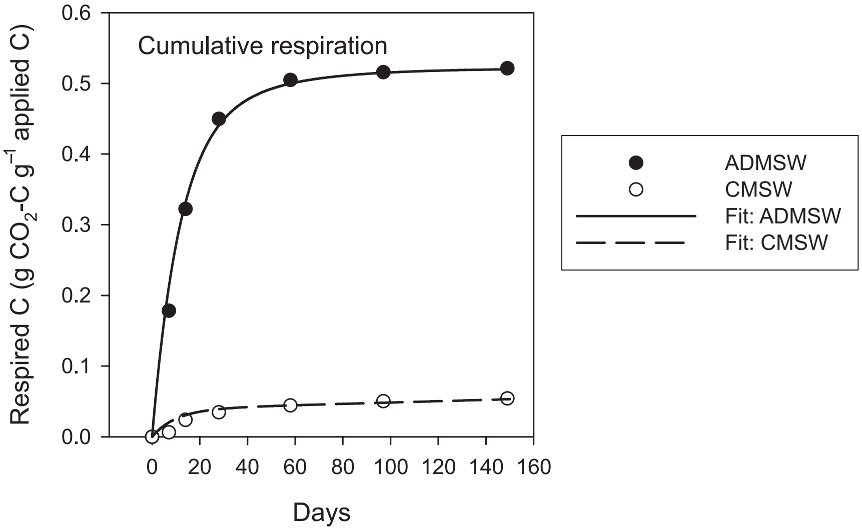

Fig. 2: Measured and fitted respiration derived from the added ADMSW and CMSW. The presented values are obtained by subtracting control from treatments values at each sampling time and given as the fraction of applied C.

Table 2: Estimated pool sizes, decay rates and C/N ratios of composted (C) and anaerobically digested (AD) MSW.

Fertilizer	Definition	Notation	Unit	Labile	Recalcitrant	Inert
CMSW	C pool fraction	MSW		0.04	0.18	0.78
	C pool decay rate	k_{MSW}	day^{-1}	0.10	5.6×10^4	0
	C/N original model			28.6	28.6	28.6
	C/N first modification			28.6	28.6	28.6
	C/N second modification			100	15.0	34.5
ADMSW	C pool size	MSW		0.42	0.10	0.48
	Decay rate	k_{MSW}	day^{-1}	0.09	0.03	0
	C/N original model			13.1	13.1	13.1
	C/N first modification			13.1	13.1	13.1
	C/N second modification			4.7×10^7	4.75	8.6

of 18% and an inert pool of 78% (Table 2). This is consistent with findings by Pansu & Thuriès (2003), who estimated the labile pool of five composts to vary between 3 and 12%, the recalcitrant pool to vary between 10 and 25% and the inert pool to vary between 63 and 87%. Bruun *et al.* (2006a) also estimated the labile pool of composted MSW to be 2%, and assumed that the remaining 98% was highly recalcitrant with a very low decay rate.

Anaerobically digested MSW

The cumulative respiration from the soil with incorporated ADMSW had a similar pattern to that from the soil with incorporated CMSW (Figure 1a). However, no initial lag phase was observed and at the end of the incubation period the respiration rate had clearly levelled off, with approximately 52% of the applied C being respired from the ADMSW (Figure 2). Hence, compared to the CMSW, the ADMSW was much more degradable. This is also evident in the parameters (Table 2) of the best fit using equation (1) (see Figure 2) of the cumulative respiration from the ADMSW, which resulted in a labile pool of 42%, a recalcitrant pool of 10% and an inert pool of 48%.

Net N mineralization

Composted MSW

Mineral N in the CMSW treatment was initially immobilized to the level of the control soil, followed by a gradual remineralization to reach a level that was slightly above the initial content after 100 days of incubation (Figure 1b). The N mineralization model (2) proposed by Bruun *et al.* (2006b) could not simulate this initial immobilization (Figure 3a). The right-hand side of equation (2) consists of two terms; $\left(\frac{a_1}{C/N} - a_2\right) \cdot C(t)_{AOM}$ and $B \cdot t$. Due to the relatively high C/N ratio (28.6) of the CMSW, the former term would lead to immobilization. Hence it is the latter term that causes

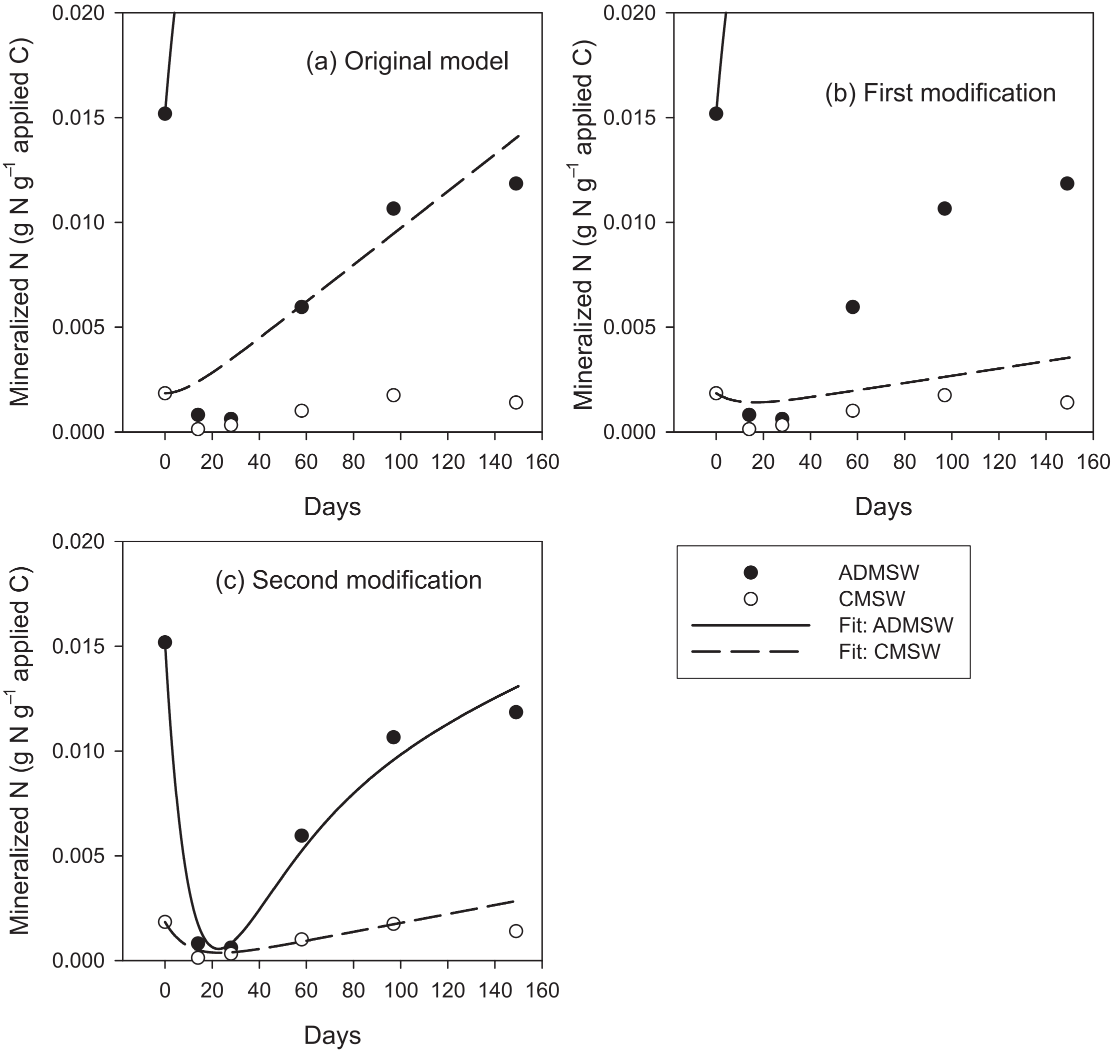

Fig. 3: Measured and fitted net N mineralization derived from the added ADMSW and CMSW. The values presented were obtained by subtracting the control value from the treatment value on each sampling occasion and expressing it as the fraction of applied C.

equation (2) to fail. The *B* value is an empirical value, but seems to be a consequence of re-mineralization occurring from the microbial biomass (see Bruun *et al.* (2006b) for a more detailed description of the *B* value). The *B* value was expressed in units of g mineralized N g^{-1} applied C day^{-1}. As a consequence, all applied N would eventually be re-mineralized from the microbial biomass. However, equation (1) suggested that 78% of the CMSW was inert (see Table 2). Thus, it would actually only be 22% of the applied N that would eventually be re-mineralized from the microbial biomass (at least within the timescale of the experiment). Hence, multiplying the *B* value in equation (2) by the fraction of decomposable C yielded equation (3), which substantially improved the simulation (Figure 3b).

$$N(t)_{\mathrm{MSW}} = \left(\frac{a_1}{(\mathrm{C/N})} - a_2\right) \cdot \mathrm{C}(t)_{\mathrm{MSW}} + \mathrm{C}(t)_{\mathrm{MSW}-f1+f2} \cdot B \cdot t \qquad (3)$$

However, the model was still unable to simulate the steep initial immobilization phase. This can largely be attributed to the C/N ratio of the CMSW, which was not large enough to cause a steep immobilization. Most soil organic matter (SOM) models divide organic matter into pools with different decay rates and C/N ratios (McGill 1996). In this study, the CMSW was divided into pools with different decay rates according to equation (1), but with equal C/N ratios (see Table 2). By modification of equation (3) into equation (4), our model was extended to also fit optimum C/N ratios for each of the three pools (see Table 2). With C/N ratios of 100 for the labile pool, 15 for the recalcitrant pool and 34.5 for the inert pool, the model was able to fit the measured N mineralization pattern adequately (Figure 3c). This could indicate that carbohydrates dominated the labile pool, whereas microbial residues dominated the recalcitrant pool, with the lower C/N ratio, and the inert pool consisted of lignified fibres.

$$N(t)_{\mathrm{MSW}} = \left(\frac{a_1}{(C/N)_{\mathrm{MSW}-f1}} - a_2\right) \cdot C(t)_{\mathrm{MSW}-f1} + \left(\frac{a_1}{(C/N)_{\mathrm{MSW}-f2}} - a_2\right) \cdot C(t)_{\mathrm{MSW}-f2} + C_{\mathrm{MSW}-f1+f2} \cdot B \cdot t \quad (4)$$

Pansu & Thuriès (2003) also found marked initial net N immobilization after incorporation of five compost types, even though the C/N ratio of the composts was rather low (11–15). To simulate this immobilization, the authors modified the N immobilization factor and the re-mineralization factor. In this way, the authors obtained an adequate model fit of the N immobilization pattern without altering the C/N ratio of the labile pool.

Anaerobically digested MSW

The ADMSW treatment also showed rapid initial immobilization, followed by re-mineralization to reach a level similar to the initial content after 100 days of incubation (Figure 1b). The original N mineralization model (2) and first modification of the model (3) could not simulate this initial immobilization (Figure 3a). A similar optimization procedure as for CMSW was carried out with respect to the simulation of the N mineralization pattern from ADMSW using equation (4). This optimization procedure resulted in C/N ratios of 4.7×10^7 for the labile pool, 4.8 for the recalcitrant pool and 8.6 for the inert pool. The very high C/N ratio of the labile pool suggests that this pool virtually does not contain nitrogen. During anaerobic digestion, substantial amounts of volatile fatty acids (VFA) can be produced (Agdag & Sponza 2005, Dearman *et al.* 2006), even after 2 month of digestion (Dearman *et al.* 2006). VFAs are generally easily decomposable when applied to soil (Kirchmann & Lundvall 1993, Sørensen 1998) and contain no N. Hence, it is very likely that the labile pool of the ADMSW to a large extent consisted of VFAs, or other easily decomposable compounds with low N contents. The remaining recalcitrant and inert pools, which both had low C/N ratios, were likely to consist of microbial residues of the ADMSW.

Implications for land management

Based on the relatively high C/N ratio of the CMSW (C/N = 28.6), some immobilization was expected. However, with a C/N ratio of 13.1 for ADMSW, the initial immobilization phase was highly unexpected. In an experiment where these same types of MSW were used in a pot experiment with spring barley (*Hordeum vulgare*), barley dry matter production was not significantly increased by MSW application (Larsen *et al.*, in press). Sufficient pre-anthesis N supply is important to obtain high cereal production (Peltonen 1993), and hence the substantial immobilization in the initial phase of the experiment probably inhibited the barley growth. If farmers are to recognize composted and anaerobically digested MSW as valuable fertilizers, it is important that these treated MSW fertilizers can be produced without variable maturity, in order to avoid initial immobilization.

Conclusions

The experiment revealed that composted and anaerobically digested MSW applied to soil had similar decomposition patterns with regard to respiration and an initial N immobilization phase followed by re-mineralization. However, on the basis of applied C, ADMSW had an order of magnitude higher degradability than CMSW. The experiment also revealed that simulation of net N mineralization, based on a simple relationship between net N mineralization and respiration developed for plant materials, was only applicable for these organic materials after significant modifications. The treated MSW types used in this experiment were not particular suitable as fertilizers due to the initial immobilization phase, which reduced the mineral N content within the first 100 days of incubation. Composted and anaerobically digested MSW can become valuable fertilizers for agriculture only if they can be produced with a higher maturity, in order to avoid initial N losses due to immobilization.

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