

Mineralization of Five Biosolids in Two Tropical Soils

Rodrigo Studart Corrêa¹; Robert E. White²; Anthony J. Weatherley²

¹ The University of Brasília - FT/EFL. C.P. 04.401 – CEP: 70.910-900 - Brasília, DF - Brazil. e-mail: rodmanga@yahoo.com.br

²The University of Melbourne - ILFR, Victoria 3010 - Australia.

ABSTRACT

This work aimed to evaluate mineralization rates of the five most common biosolids (digested sludge, composted sludge, limed sludge, heat-dried sludge, and solar-irradiated sludge) when incubated to two tropical soils - a Spodosol and an Oxisol soil. Fresh sludge and stabilized biosolids were mixed with soil samples at 0.5, 1.0, 2.0, 4.0, 6.0 and 8.0 dry t biosolids/ha and incubated at 25°C in a high humidity chamber (95% air moisture), at 12 hours light/day, during 23 weeks for a non-leaching experiment. Results have showed that all the stabilization processes altered the capacity of the fresh sludge to release mineral-N. Except solar-irradiated sludge, the stabilization processes hindered the release and accumulation of mineral-N in soils. Composting and CaO-liming were the processes that most reduced the release of mineral-N. Mineralization rates and mineral-N release from biosolids were always higher in the Ferrosol compared to Spodosol soil.

INTRODUCTION

The idea of applying organic matter, primarily containing nitrogen (N) and phosphorus (P), back into the natural cycle forms the basis of using sludge on land (Frank, 1998). There is actually a wide spectrum of sewage products internationally referred as biosolids that have been reported to improve soil physical and chemical conditions and increase plant yield (Cameron *et al.*, 1996).

Besides the significant agronomic benefits that biosolids can provide when applied to land, its use frequently encounters apprehension and even strong opposition from the general public (Forste, 1996). The reasons according to Sparkes (1990) are not only due to nuisance problems and pathogenic contents in sewage materials, but also to concerns on environmental hazards from high biosolids N and P concentrations. For such reasons, the United States Environmental Protection Agency (USEPA) has addressed potential hazards represented by disposal and beneficial use of sewage materials in its Title 40 of the Code of Federal Regulations (CFR), Part 503. It is a risk-based rule to protect public health and the environment, which describes sludge stabilization processes (sludge digestion, composting, lime stabilization, heat treatment, and solar irradiation). Stabilization processes can make biosolids safe enough for their beneficial use, and for the sake of groundwater protection, land application rates are based on matching biosolids-N with crop N-needs, namely N-agronomic rate (USEPA, 1995).

Policies worldwide will require in the next years a more intensive management of biosolids-N to avoid deleterious impacts of on the environment (Maguire *et al.*, 2000). The release of nutrients from mineralization of biosolids is therefore an important issue in plant nutrition and environmental management. Several authors stress the importance of matching the amount of nutrients available and delivered through time with crop demands in order to avoid either limitations on plant growth or losses of excess nutrient to surface and groundwater (Sims, 1990; Reed *et al.* 1995; Epstein 1997).

Laboratory incubation experiments have showed sewage sludge to be highly mineralizable (Willett *et al.* 1984). But sewage sludge stabilization processes aim to make it less putrescible, and mineralization of different stabilized biosolids probably present different capacities to release nutrients. Even mineralization rates of aerobically digested sludge are higher than of anaerobically digested sludge as the latter is more stable (Munn 1995).

When biosolids are applied to land, mineralization and nutrient transformations occur in combination with other soil processes. Mineralization rate and fate of nutrients will then depend on the soil type and site conditions. O'Dowd *et al.* (1999) stated that mineralization is a major process influencing the supply of N to plants and for leaching. Procedures involving the determination of N mineralized during incubation are considered the most satisfactory method used to estimate mineralization of organic materials in soils (Serna & Pomares 1991; van Kessel *et al.* 2000). The potential mineralization rates of different stabilized biosolids and their behavior after mixing with different soils have to be investigated for their appropriate beneficial use (Maguire *et al.*, 2000).

Thus, this work aimed to evaluate mineralization rates of the five most common biosolids (digested sludge, composted sludge, limed sludge, heat-dried sludge, and solar-irradiated sludge) when incubated to two tropical soils – a Spodosol and an Ferrosol soil.

MATERIALS and METHODS

Sludge Stabilization

A 500 kg sample of tertiary biological domestic sewage sludge was collected from a wastewater treatment plant at Bendigo shire, Victoria – Australia. The sewage sludge was analyzed in triplicate for gravimetric water content (105°C for 48 hours), bulk density (BD) (Rayment & Higginson, 1992), total carbon (total-C), total nitrogen (total-N), mineral nitrogen (mineral-N), total phosphorus (total-P), and available phosphorus (available-P). The fresh sewage sludge (Table 1) presenting 878 g kg⁻¹ moisture, BD = 1.2 Mg m⁻³, and C/N ratio = 6.2 was mixed with hardwood sawdust (96 g kg⁻¹ moisture, BD = 0.3 Mg m⁻³, and C/N ratio = 668) and woodchips (bulk agent) to achieve a C/N ratio = 25:1. Three 450 L composting piles were pitched on a sheltered cement pavement, run at 35°C - 65°C for 34 days, let to mature for another 60 days and sieved at 2 mm. Lime

treatment used CaO at 30% rate to sludge dry solids (weight/weight). Heat drying was performed in a furnace at 250°C until constant weight. The heat-dried sludge was ground and passed through a 2 mm sieve. For the solar irradiation process, three 10 kg fresh sludge samples were stored in freely drained plastic bowls under transparent plastic-covers and sunny conditions for 14 days during Melbourne's summer, with daily temperatures ranging from 12.8°C to 26.5°C. The stabilization criteria established in USEPA (1995) were achieved in all the employed processes. All stabilized biosolids were analyzed in triplicate for total-C, total-N, mineral-N, total-P and available-P using the same analytical methods for the fresh sewage sludge. Results are showed in Table 1. Analysis of variance and Tukey test were performed in GenStat® for Windows 5th edition.

Soils

Two contrasting Australian soils were selected to be amended with the biosolids: a humosesquic, aeric Podosol and an acidic, mesotrophic Ferrosol (Isbell, 1996). The soils are respectively an Orthod Spodosol and an Ustox Oxisol according to USDA (1999). A 200 kg sample of each soil was collected from nearby Melbourne, allowed to air dry for 2 weeks, and passed through a 4 mm sieve.

Mineralization Experiment

Fresh sludge and stabilized biosolids were mixed with soil samples of 1.5 kg amended at 0.5, 1.0, 2.0, 4.0, 6.0 and 8.0 dry t biosolids/ha and placed in triplicate in 1.7 L free-draining pots. Amended-soils were wetted with deionized water to their pot capacity, as described in Cassel & Nielsen (1986), and covered with plastic lids containing three 4-mm holes. Pots were incubated at 25°C ($\pm 1^\circ\text{C}$) in a high humidity chamber (95% air moisture), at 12 hours light/day, during 23 weeks for a non-leaching experiment. Three pots containing 1.5 kg blank-Podosol soil and three with blank-Ferrosol soil were placed together with the others for control purposes. Soils were mixed prior to each sampling, which occurred on day 0 and in the 1st, 3rd, 7th, 15th and 23rd weeks after the experiment started. Pots were randomized weekly and samples were sprayed on surface with deionized water every second week to replace moisture losses.

Laboratory Analysis

Blank and amended soil samples were collected and placed in a 5 °C cold room ($\pm 1^\circ\text{C}$) for the analysis of mineral-N within 48 hours after sampling. A Carbo-Erba NA 1500 analyzer was used to measure total-C and total-N by the dry combustion method. Mineral-N was analyzed by the Kjeldahl steam distillation method for ammonium-N (NH_4^+ -N) and nitrate-N (NO_3^- -N) (Rayment & Higginson, 1992). Mineralization rates were accounted based on mineral-N released in the amended soils.

Analysis of Data

Data on mineral-N concentrations during soil incubation were set on graphics and regressions were drawn for accounting mineralization rates. N-mineralized throughout 23 weeks was summed up to determine the potentially available-N (PAN). PAN can be used by plant or leached down into soil profile was calculated according to Pierzynski (1994) and Barbarick & Ippolito (2000):

$$\text{PAN} = \text{NO}_3^- \text{-N} + X \text{NH}_4^+ \text{-N} + Y \text{Organic-N} \quad \text{Equation 1}$$

where X is fraction of NH_4^+ -N that does not volatilize (often assumed to be 1) and Y is the fraction of organic-N that mineralizes. Organic-N was calculated according to Pierzynski (1994):

$$\text{Organic-N} = \text{total-N} - (\text{NO}_3^- \text{-N} + \text{NH}_4^+ \text{-N}) \quad \text{Equation 2}$$

All data were converted to oven-dry basis and statistical analyses were done in Minitab 12.1 and Systat for Windows software.

Table 1: Some agronomic characteristics of the biosolids.

Parameter	Fresh Sludge	Composted sludge	30%-CaO Sludge	250°C-dried sludge	Solar-dried sludge
		dry weight basis			
Total-C (g kg ⁻¹)	404c	283a	303b	389c	406c
Total-N (g kg ⁻¹)	65.1c	15.9a	40.1b	64.8c	65.3c
C/N ratio (w/w)	6.2a	17.8c	7.5b	6.0a	6.2a
Total-P (g kg ⁻¹)	72.1c	24.2a	50.6b	72.5c	72.6c
Mineral-N (mg kg ⁻¹)	624d	277b	93.8a	356c	803e
Available-P (mg kg ⁻¹)	268c	377d	11.9a	678e	199b
Bulk density (Mg m ⁻³)	1.2c	0.4a	1.4d	0.6b	1.3cd
		wet weight basis			
Gravimetric water (g kg ⁻¹)	878e	551b	754c	101a	819d
pH [1:5 water (w/v)]	6.4b	6.1ab	11.9d	5.8a	7.4c

Means (n = 3) with same letter within rows are not statistically different by the Tukey test (p < 0.05)

Table 2: Total-N applied to air-dry soils, based on their contents in biosolids

Equivalent dry t/ha	Fresh sludge	Composted sludge	30%-CaO sludge	250°C-dried sludge	Irradiated sludge
Total-N applied to soils as biosolids (mgN kg ⁻¹ soil)					
0.25	8.1	2.0	5.0	8.1	8.2
0.50	16.3	4.0	10.0	16.2	16.3
1.0	32.6	8.0	20.1	32.4	32.7
2.0	65.1	15.9	40.1	64.8	65.3
3.0	97.7	23.9	60.2	97.2	98.0
4.0	130.2	31.8	80.2	129.6	130.6
5.0	162.8	39.8	100.3	162.0	163.3
6.0	195.3	47.7	120.3	194.4	195.9
7.0	227.9	55.7	140.4	226.8	228.6
8.0	260.4	63.6	160.4	259.2	261.2

RESULTS and DISCUSSION

Soils amended with organic wastes are usually reported to increase mineralization rates due to the increase of available organic components and inoculation with saprophytic microorganisms (Siegenthaler & Stauffer 1991; Pascual *et al.* 1997a; Fliessbach *et al.* 2000). Mineralization rates in both soils were boosted after application of biosolids (Figures 1 - 5).

The primary factors likely to control decomposition and release of nutrients from incorporated biosolids are application rate, substrate quality and interactions with bacteria, fungi and climate (Mary *et al.* 1996; Robinson & Polgase, 1996). In that respect, the mineralization of all biosolids in Podosol and Ferrosol soils was highly influenced by the two different soils. Such a soil dependency was studied by Soni & Singh (1994) who evaluated the capacity of different soils to mineralize sewage sludge.

Concentrations of mineral-N in the Podosol soil treated with fresh sludge never reached treated-Ferrosol soil's N-concentrations during the 23 weeks of incubation, despite the equivalent rates of biosolids-N applied to both soils (Table 2). Incorporation of different rates of fresh sludge in the Podosol and subsequent mineralization brought mineral-N concentrations to 6.6 - 15.7 mg mineral-N/kg soil which accounts for a 5 - 6 fold increment in mineral-N concentrations relative to control-soil. The higher value is similar to 14.7 mg mineral-N/kg soil present in the unamended-Ferrosol soil (Figure 1b). Therefore, Podosol soil presented a limited potential for sewage sludge mineralization compared to the Ferrosol soil (Figures 1a and 1b).

Mineral-N concentrations in the Podosol treated with fresh sludge increased in a linear fashion (Figura 1a), but there was no significant difference of applying 0.5 or 1.0 dry t/ha to Podosol soils after 23 weeks of trial as both rates ended at mineral-N concentration of 6.7 mg kg⁻¹. The same applies to the range 2.0 - 6.0 dry t/ha (11.8 mg kg⁻¹) but the 8.0 dry t/ha rate finished the trial at mineral-N

concentrations significantly higher than the 2 - 6 dry t/ha range. However, for a 16 times increasing in application rate (0.5 → 8.0 dry t/ha), mineral-N concentration increased only 2.4 times (6.6 mg kg⁻¹ → 15.7 mg kg⁻¹ soil). Fresh sludge proportionally mineralized more in Podosol at low application rates (0.5 - 2 dry t/ha) than at the highest ones (6 - 8 dry t/ha). Mary *et al.* (1996) also reported relatively higher mineralization rates for the lower application rates in their work.

Ferrosol soil samples treated with fresh sludge increased N-concentrations 3 - 5 fold during incubation (Figure 1b). The 4.0 - 8.0 dry t/ha range delivered enough mineral-N to increase concentrations high enough to support crops (Rashid & Memon, 1996) yet from the 7th week. Thus, this biosolid may be able to totally substitute N-fertilizer in this soil. The highest 8.0 dry t/ha ended the trial at 58.9 (±4.1) mg mineral-N kg⁻¹ soil, which is a level suitable for most of the crops. Even the two lowest rates (0.5 - 1.0 dry t/ha) ended the trial at mineral-N concentrations (19.8 mg kg⁻¹) that Rashid & Memon (1996) heeds as suitable for most crops.

A common aspect of organic matter mineralization curves is the stabilization of cumulative mineral-N showing either mineralization stopped or significantly reduced after a certain period (Dendooven *et al.* 1995). As curves on Figures 1a and 1b are rather linear, the mineralization of the fresh sludge would probably continue in both soils if a longer time was given. The long-term mineralization of sewage sludge in soils was demonstrated by Cox & Whelan (2000) who reported N from sewage sludge incorporated to a loamy clay soil still present after five years.

The regression of mineral-N concentrations on time showed an increasing of 0.6 mg mineral-N/kg soil/week for each tone of fresh sludge dry solids applied to Ferrosol soil ($R^2 = 0.95$). For Podosol soil there was an increasing rate of 0.2 mg mineral-N/kg soil a week at the same 1 dry t/ha application rate ($R^2 = 0.92$) which made fresh sludge to mineralize three times quicker in the Ferrosol than in the Podosol soil. For the highest 8.0 dry t/ha tested in this work, such difference reached 3.8 times in favor to the Ferrosol.

Podosol and Ferrosol soils showed different mineralization patterns and rates as responses to equal application rates of composted sludge (Figures 2a and 2b). Mineral-N quickly increased in Podosol soil within three weeks of incubation (Figure 2a) while it increased mostly in the Ferrosol after the fifteenth week of trial (Figure 2b). Organic matter incorporated to soils contains fractions with weekly, monthly, and annual turnover rates and it seems that the Podosol was able to mineralize only the light organic matter fraction. Whalen *et al.* (2000) explain that the exhaustion of the most readily available-C usually slows down organic matter degradation.

Various authors cite the two stages of composted sludge mineralization in soils as a result of its highly stabilized forms of nutrients (Rodrigues *et al.*, 1995). Van Kessel *et al.* (2000) describe the compost's mineralization as biphasic because of the presence of a readily mineralizable organic pool of nutrients and a second slowly mineralizing pool. Under Podosol soil conditions, the fraction that quickly mineralized made greater contribution to inputs of mineral-N in 23 weeks, that is common in soils having low potential for organic matter mineralization (Whalen *et al.* 2000). In Ferrosol soil, mineral-N increased 1.5 times in the first 15 weeks trial and over twice from this to the 23rd week.

Although mineralization rates of composted sludge in Ferrosol soil were much higher, doses 0.5 -1.0 dry t/ha did not significantly ($p = 0.05$) increase mineral-N relative to the control-Ferrosol (Figure 2b). Control-Ferrosol soil increased mineral-N from 5.0 (± 0.2) to 14.7 (± 1.8) mg kg⁻¹ in 23 weeks of incubation, whilst 1.0 dry t/ha amended-soils departed from 5.3 mg kg⁻¹ to reach 15.3 mg kg⁻¹ after the same period. Thus, Ferrosol had to receive at least 2.0 dry t/ha of composted sludge to significantly increase mineral-N concentrations by approximately 30%. Doses of 6.0 and 8.0 dry t/ha could increase mineral-N by 40% and 65%, respectively, relative to the control-Ferrosol.

Mineralization rates of composted sludge in sandy soils are frequently reported as low: 10% after 160 days incubation at 25°C in Smith *et al.* (1998b) and less than 20% after a year at 14°C in Leifeld *et al.* (2001). Saviozzi *et al.* (1999) consider composted sludge more adequate to restore soil organic matter than sewage sludge as the former lasts longer in soil as a result of its higher degree of stabilization. Composted sludge has mineralized twice as quicker in the Ferrosol than in the Podosol soil.

The mineralization of 30%-CaO sludge in soils occurred mostly until the 7th week of incubation, from which mineral-N increased little (Figure 3a and 3b). The 30%-CaO sludge showed amongst the biosolids in this work the highest mineralization rates in Podosol soil: mineral-N doubled each week until the 15th week and from this mineral-N increased a further 20%. Concentrations of mineral-N in Podosol samples treated with 30%-CaO sludge increased from 4 to 6 times during incubation and reached values up to 21 times higher compared to control.

According to Sloan & Basta (1995), the liming of sewage sludge usually enhances mineralization rates when pH set within 5 - 7. But the two highest application rates (6.0 and 8.0t dry solids/ha) were exceptions as most of the mineralization occurred between the 7th and 15th weeks. It was probably a pH influence since soil pH increased pH to 7.0 - 7.5 while lower rates never increased pH beyond 6.5.

A high pH buffering capacity of Ferrosol soil enabled it to receive up to 8.0 dry t/ha of 30%-CaO sludge without significantly change its pH. It suggests this soil could receive higher loads of limed-sludge without major changes in pH related-chemical characteristics, such as P availability. However, Ferrosol samples amended at 0.5 dry t/ha ended the trial having mineral-N concentrations approximately 10% lower than the control-Ferrosol soil. Application rates between 1.0 - 4.0 dry t/ha could not significantly increase mineral-N relative to control. A significant 8% mineral-N increase ($p = 0.05$) started to occur from 6.0 dry t/ha rate. At 8.0 dry t/ha rate, mineral-N increased by 35% relative to the control-Ferrosol (Figure 3b). The 30%-CaO sludge's capacity to increase mineral-N in Ferrosol remained at one-third compared to the fresh sludge.

Overall, a dry tone of 30%-CaO sludge increased mineral-N at 0.2 mg/kg soil/week in the Podosol and 0.4 mg/kg soil/week in Ferrosol soil. The former rate is similar to fresh sludge in the Podosol soil but the last one is approximately half the mineralization rate of fresh sludge in the Ferrosol. Therefore, lime enhanced mineralization in the Podosol soil and delayed it in the Ferrosol soil.

The 250 °C-heat drying process certainly sterilized fresh sludge and deprived it of microorganisms. Enzymatic activities to break down organic components into available nutrients are highly dependable on microbial activity (Pascual *et al.* 1997a). Possibly due to shortage of microorganisms and lower dissolution capacity, a tone of 250°C-dried pellets reached only 54% of mineral-N concentrations in the Podosol compared to the fresh sludge, despite both biosolids have similar contents of nutrients at dry matter base (Table 1). Figures were better in the Ferrosol as mineral-N reached 61% of fresh sludge's concentrations.

Despite of it, Podosol soil responded well to the incorporation of different rates of 250°C-dried sludge. There was a linear increase in mineral-N through the time from application rates of 4.0 dry t/ha. Application rates ≤ 2.0 dry t/ha resulted in very gentle slopes as the release of mineral-N was very slow (Figure 4a). The highest 8.0 dry t/ha rate finished the trial at 12.3 (± 0.8) mg kg⁻¹, which is approximately three times higher than the control and 30% higher than the amount released by 4.0 - 6.0 dry t/ha rate.

Mineralization of 250°C-dried sludge in the Ferrosol showed a similar pattern to that shown by the composted sludge. Mineral-N increased at higher rates after 15 weeks of incubation than in the first half of trial. However, the 250 °C-dried pellets increased Ferrosol's mineral-N concentrations 46% higher than composted sludge, that is a consequence of the pellets' higher initial mineral-N content (Table 1). Similar fact occurred in the Podosol, where mineralization rates of dried-pellets were half compared to the composted sludge, but mineral-N concentrations increased 40% higher in

Podosol treated with the former biosolid. Therefore, from the practical point of view, both of biosolids mineralize slower in soils than their raw material (fresh sewage sludge). But the 250°C-dried pellets were more effective to increase mineral-N concentrations than equivalent dry tonnage of composted sludge.

Solar-irradiated sludge at 6.0 - 8.0 dry t/ha application rates were the treatments that most increased mineral-N in the Podosol soil, especially because these two highest doses showed a distinguished increase in mineral-N concentrations relative to the lower application rates (Figure 5a). Controversially this biosolid had one of the lowest mineralization rates in this soil (Table 3) and its high mineral-N concentrations (Table 1) must be the cause of such a high mineral-N input. Mineral-N concentrations in the Podosol treated with solar-irradiated sludge reached up to 19.4 mg/kg soil against a value 36% lower for the fresh sludge at the same 8 dry t/ha application rate. Wen *et al.* (1997) also reported higher mineral-N concentrations in soils incubated with irradiated sludge than with fresh sludge.

Ferrosol soil treated with solar-irradiated sludge reached similar N-concentrations and increasing patterns to the fresh sludge (Figures 1b and 5b). Both biosolids applied to Ferrosol linearly increased mineral-N through the 23 weeks to end the trial at the highest mineral-N concentrations in this soil (57.5 mg kg⁻¹). According to Smith *et al.* (1998a), storage effectively stabilizes organic-N in sewage sludge making the organic matter more resistant to further mineralization in soil. This statement applies to the Podosol soil but for the Ferrosol, soil environment prevailed as these two biosolids showed the two highest mineralization rates in this soil.

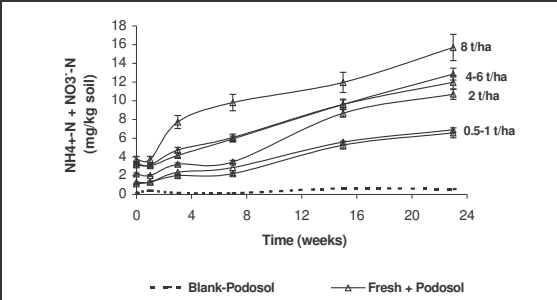


Figure 1a: Fresh sludge-amended Podosol soil in 23 weeks incubation

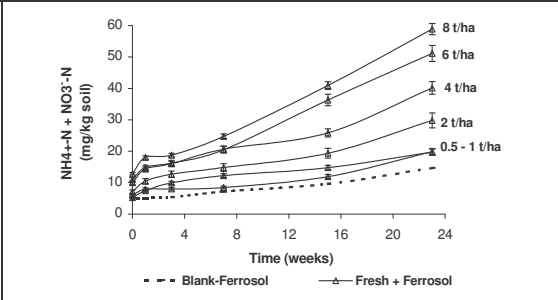


Figure 1b: Fresh sludge-amended Ferrosol soil in 23 weeks incubation

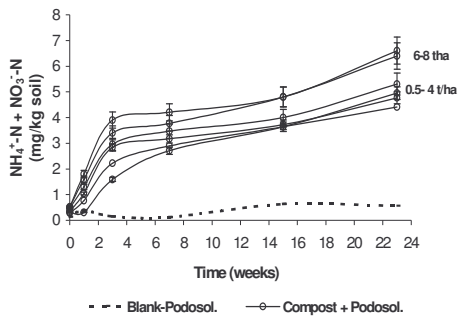


Figure 2a: Composted sludge-amended Podosol soil in 23 weeks incubation.

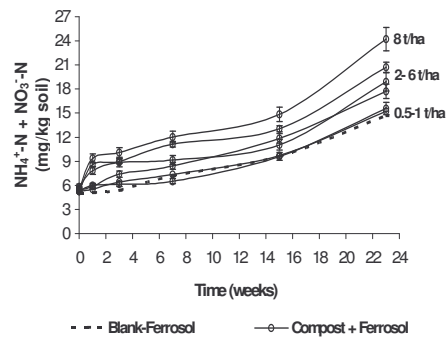


Figure 2b: Composted sludge-amended Ferrosol soil in 23 weeks incubation

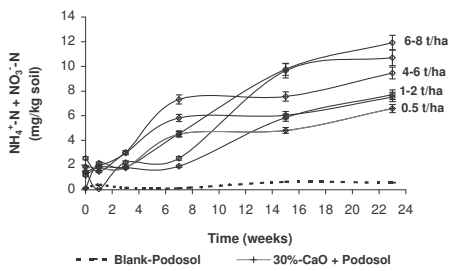


Figure 3a: 30%-CaO sludge-amended Podosol soil in 23 weeks incubation

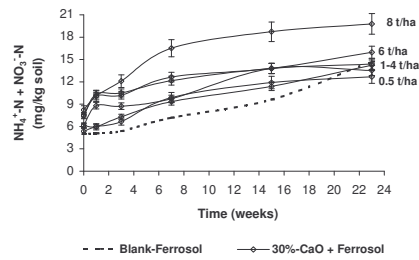


Figure 3b: 30%-CaO sludge-amended Ferrosol soil in 23 weeks incubation

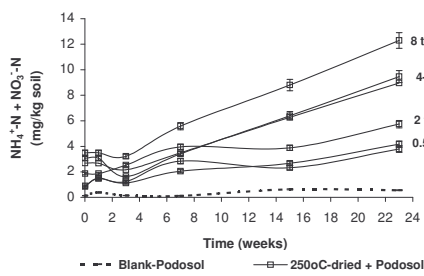


Figure 4a: 250°C-dried sludge-amended Podosol soil in 23 weeks incubation.

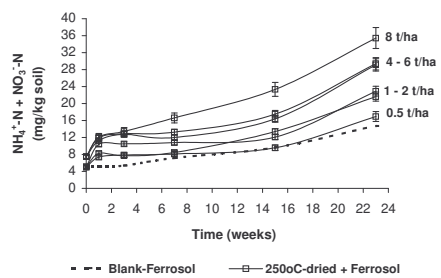


Figure 4b: 250°C-dried sludge-amended Ferrosol soil in 23 weeks incubation.

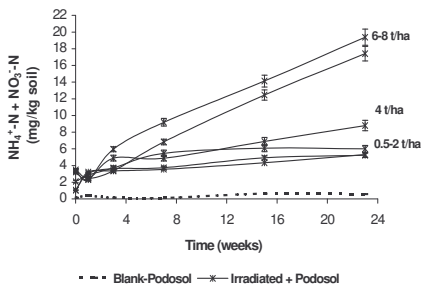


Figure 5a: Solar-irradiated sludge-amended Podosol soil in 23 weeks incubation.

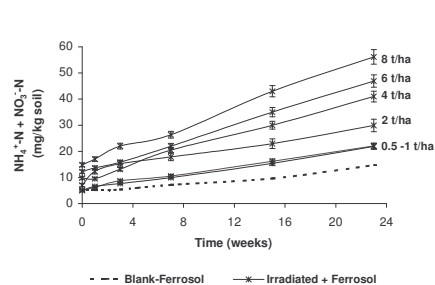


Figure 5b: Solar-irradiated sludge-amended Ferrosol soil in 23 weeks incubation

Many patterns for the mineralization of biosolids have been described in the literature, since soil type, temperature of incubation, biosolids' N content, C/N ratio, and time influence the kinetics of organic matter degradation (Dendooven *et al.* 1995; van Kessel *et al.* 2000). Zero-order and first-order functions can usually explain the biggest part of mineralization of organic materials added to soils (Dendooven *et al.* 1995; Mary *et al.* 1996; van Kessel *et al.* 2000). In this work, zero-order functions (linear equations) could explain from 71% to 99% of the mineralization of biosolids in both Podosol and Ferrosol soils.

After 23 weeks of soil incubation, between 10% and 28% of organic-N in biosolids mineralized in the Podosol and from 32% to 82% in the Ferrosol soil (Table 3). Van de Graaff (1998) considers soil the most effective medium for mineralizing decomposable substances, which could be confirmed for biosolids, particularly when applied to Ferrosol soil. High mineralization rates of organic materials are frequently reported in soils presenting higher clay content (Fliessbach *et al.* 2000), which is desirable for both the supply of nutrients to plants and degradation of hazardous organic substances.

The highest percentage of organic-N mineralized in the Podosol referred to the composted and 30%-CaO sludge (Table 3). However, their lower N content resulted in PAN inputs inferior to that from fresh sludge. On the other hand, the high N content in 250°C-dried pellets showed the lowest mineralization rate in this soils and PAN input was half of that release by the fresh sludge. Approximately 17% of fresh sludge organic-N at 1 dry t/ha application rate had mineralized after 23 weeks of incubation in the Podosol. This biosolid had the highest mineralization rate over the period and as a result, fresh sludge showed the highest PAN input in this soil. As far as a N-source is the concern, fresh and solar-irradiated sludge were the best options for the Podosol soil.

Composted sludge applied to Ferrosol soil mineralized 82% of its organic-N but the potentially available nitrogen (PAN) input was one of the lowest measured (Table 3). Considering the initial values of mineral-N in compost-amended soils, mineralization of organic-N incremented at most an extra 2 mg kg⁻¹ in Podosol soil and 9.5mg kg⁻¹ in Ferrosol soil. The highest mineral-N concentration achieved in composted sludge-amended Podosol soil (6.6mg kg⁻¹) is similar to the value showed by the 0.5 dry t/ha of fresh sludge in the same soil.

Fresh and solar-irradiated sludge mineralized approximately half the organic-N in Ferrosol soil and PAN inputs were the greatest ones (Table 3). Despite only 32% of dried-pellets' organic-N mineralized in Ferrosol soil, PAN input was higher than composted and 30%-CaO sludge in this soil. Pascual *et al.* (1997b) stated that different rates of mineralization amongst sewage materials are consequence of different stabilization processes. According to them, the less stable is an organic material the bigger the soil biological activity and its mineralization in soils. However, organic-N content was of greater importance in the Ferrosol for PAN input than the stabilization degree of the biosolids.

Ferrosol amended with biosolids presented a better C/N ratio range (23-30:1) than amended Podosol soils (12-20:1) for mineralization to occur. Thus, mineralization rates were correlated with C/N ratios ($R^2 = 0.56$) in the Ferrosol but not in the Podosol ($R^2 = 0.002$). Mary *et al.* (1996) pointed out the importance of appropriate soils' C/N ratios to degrade organic materials. There was not any correlation between mineralization rates and total-N concentrations in both Podosol and Ferrosol soils besides it was drawn by Cox & Whelan (2000) in their work. The mineralization of biosolids in Ferrosol soil was more predictable and efficient relative to the Podosol soil. Iakimenko *et al.* (1996) concluded that among various factors soil type was the most important for N mineralization of sewage sludge, followed by application rate.

Mary *et al.* (1996) calculated that laboratory experiments underestimate field mineralization trials by 25% under northern France environment. Zagal (1994) concluded from his incubation experiment that amounts of N-mineralized in planted soil during 43 days were comparable to N-mineralized in unplanted soils incubated for 210 days. Therefore, under planted field conditions mineralization rates will probably be higher than the results found here.

Table 3: PAN in biosolids-amended soils at 1.0 dry t/ha after 23 weeks of incubation

Biosolid	NH ₄ ⁺ -N at day 0 (mg/kg soil)	NO ₃ ⁻ -N at day 0 (mg/kg soil)	Organic-N mineralized	Mineralization rate (mgN/kg soil/week)	PAN input after 23 weeks of incubation (mg/kg soil)
Podosol soil					
Fresh	1.18	0.14	17%	0.24	5.6
Composted	0.16	0.15	28%	0.20	4.6
30%-CaO	2.55	0.0	25%	0.22	4.9
250°C-Dried	1.15	0.02	10%	0.13	3.0
Irradiated	1.05	0.0	13%	0.18	4.2
Ferrosol soil					
Fresh	5.15	0.08	45%	0.63	14.5
Composted	5.09	0.18	82%	0.43	9.9
30%-CaO	6.13	0.0	40%	0.35	8.1
250°C-Dried	4.96	0.06	32%	0.52	11.9
Irradiated	5.08	0.0	52%	0.74	16.7

CONCLUSIONS

All the stabilization processes used in this worked (composting, CaO-liming, heat-drying and solar irradiation) altered the capacity of the fresh sludge to release mineral-N. Except solar-irradiation, the stabilization processes hindered the release and accumulation of mineral-N. Composting and CaO-liming were the processes that most reduced the release of mineral-N.

Potentially available-N (PAN), percentage of organic-N mineralized, and mineralization rates were always higher in Ferrosol than in Podosol soil.

Fresh and solar-irradiated sludge presented the highest PAN in Ferrosol soil. This soils treated with 250°C-dried sludge came on second place, followed by composted and 30%-CaO sludge. But not only the composted sludge released more mineral-N than 30%-CaO sludge in the Ferrosol, but also the former tends to keep increasing after 23 weeks whilst 30%-CaO sludge had already peaked before the end of the experiment.

Except 30%-CaO sludge, the biosolids could not display their full mineralization potential due to the relative short-term experiment. The premature exhaustion of N from 30%-CaO sludge was a common characteristic in both soils. Despite the low capacity of composted sludge to increase mineral-N, it was the most degraded biosolid in both Podosol and Ferrosol soils. On the other hand, 250°C-dried sludge mineralized little, but it has high amounts of N to be delivered on a longer-term basis.

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