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Full Length Research Paper

Carbon and nitrogen mineralization from selected organic resources available to smallholder farmers for soil fertility improvement in Zimbabwe

J. Nyamangara[1]*, F. Mtambanengwe[1] and C. Musvoto[2]

[1]Department of Soil Science and Agricultural Engineering, University of Zimbabwe, P. O. Box MP167, Mount Pleasant, Harare, Zimbabwe.

[2]Institute of Environmental Studies, University of Zimbabwe, P. O. Box MP 167, Mount Pleasant, Harare, Zimbabwe.

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A study was conducted to assess the N release dynamics of three organic resources widely used by smallholder farmers in sub-Saharan Africa to improve soil fertility. Addition of cattle manure, miombo and mango (*Mangifera indica*) litter to soil increased ($p < 0.05$) CO_2-C evolution compared to unamended soil. Cumulative CO_2-C evolution in all the three organic amendments followed first order kinetics ($R^2 = 0.89 - 0.99$). Slight N mineralization occurred when cattle manure was added to soil and addition of manure in combination with mineral N had no effect on the extent of N mineralization. Compared to unamended soil, miombo litter induced net immobilization of N for 60 days and thereafter net N mineralization occurred. Both untreated and composted mango litter immobilized N (up to 15 mg N kg^{-1}) during the 77 day incubation. It was concluded that all the three organic resources were poor and inadequate sources of N for plant growth in the short term and should therefore be supplemented with mineral N to reduce N immobilization and consequent N deficiency in plants. However the organic resources may improve the soil physical environment and also contribute to soil organic matter build up in the long term.

Key words: Cattle manure, *Mangifera indica,* miombo litter, N mineralization and immobilization.

INTRODUCTION

The majority of soils in the smallholder areas of Zimbabwe are inherently infertile (Campbell et al., 1997; Nyamangara et al., 2000) and sustainable cultivation is not feasible without addition of plant nutrients. Mineral fertilizers are not affordable to most of the smallholder farmers in Sub-Saharan Africa (SSA) including Zimbabwe (Quiñones et al., 1997). Consequently farmers are left with very limited options and therefore concentrate their effort on organic nutrient sources. Available forms of organic nutrient sources often include farmyard manure (Mugwira and Murwira, 1997), crop residues (Campbell et al., 1998), tree litter collected from woodlands and litter from trees growing in arable areas (Nyathi and Campbell, 1993) and green manures (Giller, 1998). However, the nutrient release dynamics of some of the organic resources used by the smallholder farmers is not well understood. An understanding of the nutrient release dynamics would enable farmers to manage the organic resources in a manner that optimises nutrient uptake and ultimately crop productivity. An organic resource data-base for organic inputs normally applied to soil in tropical agroecosystems has been developed (Palm et al., 2001) but still requires extensive validation.

Cattle manure is the major organic fertilizer used by smallholder farmers in Zimbabwe (Campbell et al., 1998).

*Corresponding author. E-mail: jnyamangara@yahoo.co.uk, jnyamangara@agric.uz.ac.zw.

The Alvord system, which is based on the application of manure at 37 t ha^{-1} to maize (staple crop) in a four-year rotation, has been widely recommended to and adopted by many smallholder farmers in Zimbabwe (Mugwira and Shumba,1986). However, the effectiveness of the manure is often limited by poor quality (low nutrient content) and immobilization of N which occurs during early plant growth following manure application (Murwira and Kirchmann, 1993).

Trees, both indigenous and exotic, are a feature of cultivated areas in most smallholder farming areas in SSA (Kater et al., 1992; Rhoades, 1995). Trees are re-tained in or planted in arable areas for different reasons, but they also influence soil properties. Trees have been reported to increase soil organic matter (Frost et al., 1986; Kamara and Haque, 1992), exchangeable bases and P (Kamara and Haque, 1992) in soil under their ca-nopy, although the effect is limited to surface horizons (Kater et al., 1992). Although the mechanism of soil enrichment under tree canopies remains largely unex-plained, some studies have attributed the enrichment to litter accumulation under trees (Kessler, 1992), leachates from tree canopies, nutrient inputs from atmospheric deposition and transport by tree roots from rooting zones outside the tree canopy (Nair, 1987; Young, 1989), and droppings from animals nesting and resting under trees (Robinson, 1986; Belsky et al., 1989).

In the smallholder farming areas of Zimbabwe, partially decomposed litter from natural miombo woodlands is used to amend soils (Nyathi and Campbell 1993). Freshly fallen miombo leaf litter has average C and N contents of about 42 and 1.2% (C:N = 35), respectively (Mtambanengwe, 2000), but C and N mineralization potential and decomposition patterns of plant litter are variable depending on the chemical composition (Mtambanengwe and Kirchmann, 1995). During decomposition, organic material changes in both its physical and chemical structure, thus modifying the substrate's decomposability (Swift et al., 1979).

Mango (*Mangifera indica*) trees are planted widely in agroforestry systems in Zimbabwe and many parts of the world (Musvoto, 1999) and contribute litter to the systems in which they occur. In the smallholder farming areas of Zimbabwe, litter from mango trees planted outside cropping areas is often transferred to croplands to ameliorate soils (Musvoto, 1999).

The aim of this study was to determine the decomposition and N release patterns from three organic resources widely available to smallholder farmers in Zimbabwe, and SSA in general, namely cattle manure, miombo and mango litter. Knowledge of the N release patterns of these organic resources is essential in order to increase N uptake efficiency and crop productivity, by synchronising N release from the organics and crop uptake. It was hypothesized that the organic resources induced net N mineralization when applied to soil.

MATERIALS AND METHODS

Site description

The study was conducted using soils from two sites. The incubation experiments were conducted separately as part of a project on management of soil organic matter in sub-humid smallholder areas of Zimbabwe. Soils used for the manure and mango litter incubation studies were collected from Domboshawa Training Centre (17° 36 'S and 31° 19 'E) and Mangwende Communal Area, respectively. Soil for the miombo litter incubation study was collected from Grasslands Research Station (18° 10'S and 31° 30'E). The soils at all the sites were derived from granite, well drained, moderately leached and classified as Fersialitic (5G) (Zimbabwe), Typic Kandiustalf (USDA) or Haplic Lixisol (FAO) (Nyamapfene, 1991). It was assumed that the differences in clay content in the three sandy soils were not significant enough to affect C and N dynamics and therefore results could be compared. All the sites are found in Agro-ecological Natural Region II characterized by unimodal rainfall (800 - 1000 mm per annum, October - April).

Cattle, miombo and mango litter preparation and analysis

Cattle manure was aerobically composted and was collected from Mangwende smallholder farming area in North- eastern Zimbabwe. Mixed litter from the floor of miombo woodland dominated by *Brachystedia spiciformis* was collected during the dry season period of July to September 1994. The mixed litter comprised mostly of unrecognisable materials at various stages of decomposition including bark, insect debris, lichens and fungi (Mtambanengwe, 2000).

Mango litter was collected from mango- maize agroforestry systems on five farms (five trees per farm) in Mangwende smallholder area during August and September 1994. The mango litter consisted of fallen senescent leaves gathered from the ground. The litter was thoroughly mixed and aerobically composted (180 days at 25°C) in plastic bins with perforated sides and tightly fitted lids.

The three organic materials were oven-dried, milled to pass through a 2 mm sieve and then analysed for total C (Nelson and Sommers, 1982) and total N (Bremner and Mulvaney, 1982). Soil and ash content in cattle manure was determined using a method described by Nyamangara (2001). The acid detergent fibre method was used to determine lignin content, and the Folin-Denis method was used for analysis of total polyphenols in mango and miombo litter (Anderson and Ingram, 1989; Quarmby and Allen, 1989). Soluble phenolics were determined gravimetrically by precipitation with trivalent ytterbium (Reed et al., 1985).

Soils used in the study were analysed for texture, pH, organic C, total N, exchangeable bases and cation exchange capacity using standard methods (Okalebo et al., 2002).

Incubation procedure

Ten grams of soil were weighed into 100 ml incubation tubes and thoroughly mixed with 30 g of acid washed 30 - 60 mesh quartz sand to which about 6 ml of distilled water was added (Bremner, 1965). The mixture was pre-incubated for 6 days at 25°C before imposing treatments. Application rates of manure, mango and miombo leaf litter were based on surveys which indicated the rates farmers in the study areas normally used (Mtambanengwe, 2000; Musvoto, 1999; Nyamangara, 2001).

For cattle manure, the treatments were: no addition (control), 5 mg manure g^{-1} soil (M), and M + 20 µg N g^{-1} soil corresponding to 30 kg N ha^{-1} (NH_4NO_3) on a soil dry weight basis. For mango and miombo litter, 100 mg (dry weight basis) of ground material was

Table 1. Some chemical and physical properties of the 0 - 20 cm layer of the experimental soils.

Site	Texture (%)C/S/S	Soil pH $CaCl_2/H_20$	Organic C (%)	Organic N (%)	C:N	TEB (me%)	CEC (%)
Domboshawa training centre	5/3/92	4.7/5.4	0.40	0.03	13.3	0.85	1.70
Grasslands research station	15/7/78	5.1/5.7	1.11	0.10	11.0	2.1	2.6
Mangwende smallholder area	6/5/89	4.5/5.2	1.40	nd	nd	2.84	nd

C/S/S - clay/silt/sand. Nd - not determined.

Table 2. Selected chemical properties of the organic materials used in the incubation study

Organic material	C(%)	N(%)	C:N	Lignin(%)	Cellulose(%)	Polyphenols(%)
Cattle manure	11.3	0.62	18.3	nd	nd	nd
Miombo mixed litter†	42.0	1.94	21.6	7.82	19.8	0.8
Mango litter						
Untreated	41.74	0.55	75.9	10.86	19.03	18.6
Composted	39.48	0.76	52.0	13.93.	20.84	7.6

†Mixed fragments comprising of mostly unrecognisable leaf litter, leaflet materials, flowers, twigs, bark, lichens, insect debris and soil organic matter.

added to the soil-sand mixtures.

For all the treatments, one series of containers was prepared for measurement of KCl-extractable N at different times during incubation (up to 77 days). A second series was prepared to determine the C mineralization patterns of the different treatments during the incubation period (25°C). In the second series, small vials con-taining 10 ml of 0.5 M NaOH were placed inside the tubes on top of the soil to absorb evolved CO_2. The tubes were closed with air-tight rubber stoppers to avoid drying and minimize gaseous losses. Aerobic conditions were maintained during the incubation period by opening the tubes for several minutes, every third day. The CO_2 traps were periodically recovered and evolved C determined by back-titrating excess NaOH with 0.1M HCl.

Available N was determined colourimetrically after extraction with 2 M KCl (Keeney and Nelson, 1982). All treatments in both series were replicated three times.

RESULTS

The experimental soils were generally acidic, and the Domboshawa soil had a very low organic matter (Table 1). Cattle manure contained high concentrations of soil plus ash (84.5%), and consequently the C and N concentrations were lower (Table 2) than normally reported for manures. Expressing manure C and N concentration on a soil- and ash-free basis showed that the values were 61.6 and 3.38%, respectively.

The N content of mixed miombo woodland litter was relatively high, 1.94% with a C:N ratio of 22 while lignin and polyphenols were in the low range. Cellulose content of the litter was high and not significantly different from that of mango litter (Table 2) . Both composted and untreated mango litter contained low levels of N (0.76 and 0.55 % respectively). Composting raised the lignin and cellulose contents and lowered the carbon and polphenol contents of mango litter (Table 2).

C mineralization

The addition of cattle manure resulted in a significant ($p < 0.01$) increase in CO_2-C evolution when compared with soil (Figure 1). Combined addition of manure and mineral N fertiliser resulted in lower CO_2-C evolution than from the manure amended soil but was still higher than from unamended soil (Figure 1). Data on cumulative CO_2-C evolution was best described by the first order function (R^2 = 0.93 - 0.99) (Table 3a). Addition of mineral N fertiliser reduced the exponential proportion of the C mineralised in manure showing that the fertiliser affected the initial stages of manure decomposition (Table 3a).

Applying miombo litter to soil significantly ($p < 0.01$) increased CO_2-C evolution compared to soil without any amendment (control) (Figure 2). The rate of C mineralization followed first order kinetics (R^2 = 0.91 - 0.99) (Table 3b).

Applying mango litter to soil significantly ($p < 0.01$) increased CO_2-C evolution compared to soil without any amendments (Figure 3). Composted mango litter evolved less CO_2-C in comparison with untreated mango litter ($p < 0.01$) (Figure 3). Net C mineralization was 47% of the C added in untreated litter and 37% in composted litter. The pattern of CO_2-C evolution in the two litter treatments and the control followed the first order kinetic function (R^2 =

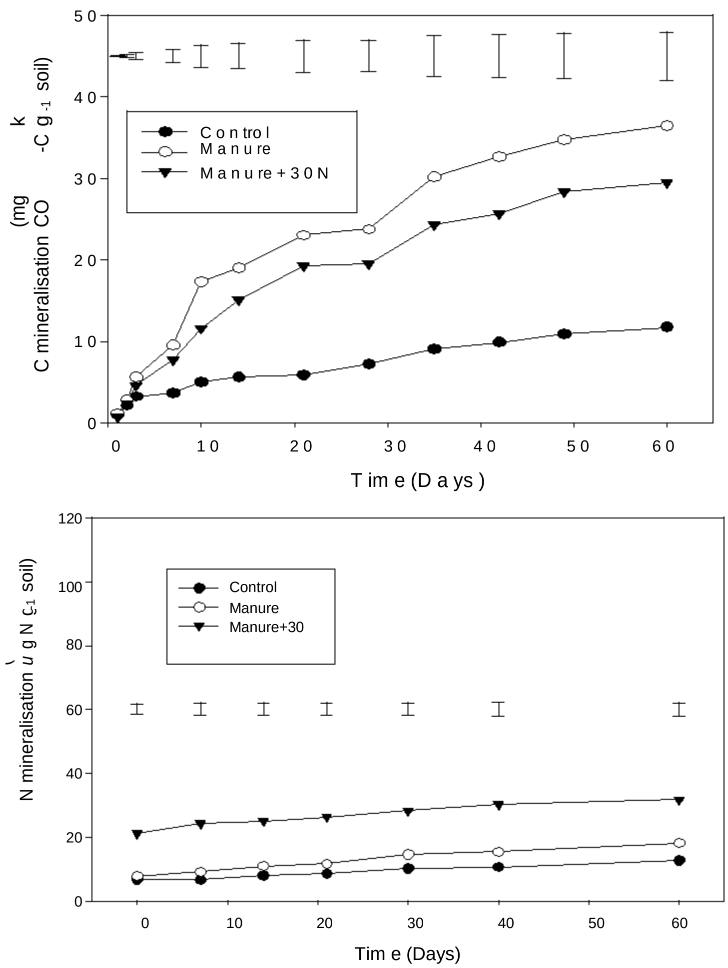

Figure 1. Mineralization of carbon and nitrogen from soil amended with aerobically composted cattle manure and mineral N.

Table 3. Parameter values and coefficients of determination for the C mineralization kinetics of cattle manure, miombo and mango litter.

(a) Cattle manure

Treatment	Course of CO_2 evolution	Exponentially mineralizable carbon C_E (mg kg^{-1})	Rate constant k (Day^{-1})	Half life (Days)	Correlation coefficient R^2
Control	Exponential	11.99	0.043	16.04	0.93
Manure	Exponential	38.12	0.046	15.21	0.98
Manure+30 kg N ha^{-1}	Exponential	31.50	0.043	16.30	0.99

b) Miombo litter.

Treatment	Course of CO_2 evolution	Exponentially mineralizable carbon C_E(mg kg^{-1})	Rate constant k (Day^{-1})	Half life (Days)	Correlation coefficient R^2
Control	Exponential	0.05	0.01	11.82	0.91
Mixed litter	Exponential	57.02	0.002	2444	0.99

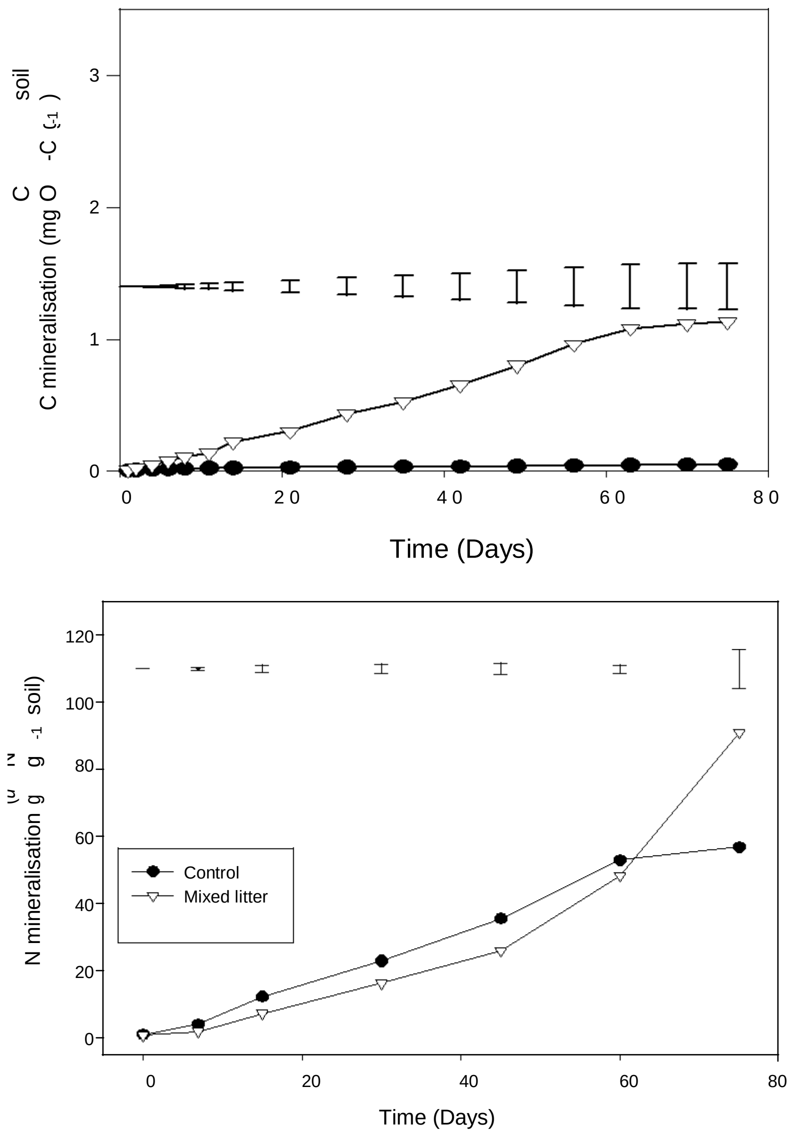

Figure 2. Mineralization of carbon and nitrogen from soil amended with different types of miombo litter.

0.89-0.99) (Table 3c).

N mineralization

There was a slight net N mineralization in all the manure treatments (Figure 1). However, there was no significant ($p < 0.05$) difference in N mineralization between the control and the manure treatments. The addition of N fertilizer to the manured soil resulted in a proportional increase in KCl-extractable N in the treatments before incubation (Figure 1). There was no interaction between the manure and the mineral N fertilizer during the 60-day incubation period.

The N mineralization rate of unamended soil was positive and in most cases higher than that of soil amended with miombo litter (Figure 2). The miombo litter immobilised N up to 60 days following when there was net N mineralization (Figure 2).

After 77 days of incubation, the control mineralised more nitrogen ($p < 0.05$) than soil amended with untreated or composted mango litter (Figure 3). The cumulative inorganic N content of soil amended with composted litter (29.86 μ g N g^{-1} soil) was significantly higher ($P < 0.05$) than that of soil amended with untreated litter (9.70 μg N g^{-1} soil). Composting slightly reduced N immobilisation by mango litter but this was not significant ($p < 0.05$).

(c) Mango litter.

Treatment	Course of CO_2 evolution	Exponentially mineralizable carbon C_E (mg kg^{-1})	Rate constant k (Day^{-1})	Half life (Days)	Correlation coefficient R^2
Soil only	Exponential	0.55	0.06	17.33	0.89
Untreated	Exponential	2.48	0.04	48.04	0.94
Composted	Exponential	3.05	0.01	11.30	0.99

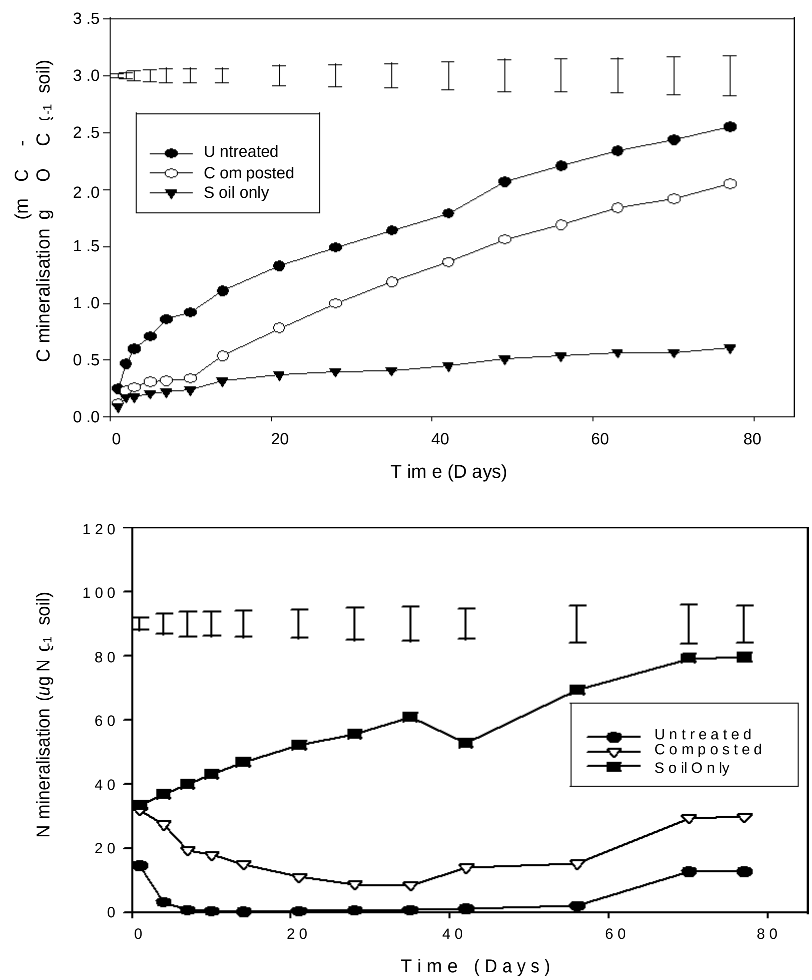

Figure 3. Mineralization of carbon and nitrogen from soil amended with mango litter treated in different ways.

DISCUSSION

The differences in C and N mineralization pattern in the control treatments of the different organic resources were mainly attributed to the differences in the qualities of the organic resources. The dilution effect of sand was uniform across the treatments and was meant to ensure aerobic mineralization during incubation. The sand is inert and therefore does not contribute to the mineralization dynamics (Bremner, 1965; Nyamangara, 2000).

Cattle manure

The presence of high soil contents in cattle manures from smallholder farms in Zimbabwe, and SSA in general, needs to be considered when using cattle manure. Most of the soil is mixed up with the manure by the trampling effect of cattle in the kraal during the rainy season (Mugwira and Murwira, 1997).

The proportion of CO_2-C mineralised from the cattle manure studied was relatively low when compared to other animal manures (Kirchmann, 1991). This was attributed to the C stabilisation which occurred during aerobic decomposition of the manure during storage. Stabilisation of C during aerobic decomposition has also been reported elsewhere (Murwira and Kirchmann, 1993; Hadas and Portnoy, 1994; Hadas et al., 1996).

This study showed that the manure, which is typical of those from smallholder areas of Zimbabwe, induced no net changes in mineral N in soil. Therefore, aerobically composted manures from smallholder areas in Zimbabwe, and similar farming systems in SSA, are poor and insufficient N sources for crop production in the short term. There is need to investigate how the addition of mineral N fertilizer depresses C mineralization, that is, which C constituents of the manure are affected by the N and how does mineral N addition affect the stabilization efficiency of manure C in soil?

Miombo litter

Generally, leaf litter has been described as high quality because of its high N and low lignin contents (Young, 1989) and thus decomposes easily. However, the leaf litter from the miombo woodland is considered as slow decomposing in comparison with leaf and leaflet materials from N-fixing leguminous tree species (Nyathi and Campbell, 1993).

This study demonstrates that miombo litter may be a poor source of N for plant growth in short- term. The net-release pattern shown after 60 days may have implications on its use as a nutrient source. For a current crop, the results imply that some mineral N may be required to offset the negative effects of immobilization thus reducing the period of N deficiency during early crop growth. The Decision Guide for organic N management (Palm et al., 2001) recommends that such low N, low lignin containing materials may be used in combinations with N fertilizer or added to compost. Future research efforts should perhaps be directed at investigating the residual role of such materials on a successive crop. Although potential N contributions from the sandy soils appeared to be somewhat low, observed crop responses on smallholder farms in the absence of external nutrient additions may be due to N mineralized from native soil organic matter.

Mango litter

Composted litter had lower decomposition rates in comparison with untreated litter. Composted litter contained less C than untreated litter having already lost 3% C during composting. The C in composted litter was, however, more resistant to decomposition than the C in untreated litter. Kirchmann (1991) also reported lower CO_2-C evolution from composted than from fresh animal manures due to the stabilisation of C in animal manures after composting.

In this study, contrary to the findings of Kirchmann (1991), Zaccheo et al. (1993), and Crippa and Zaccheo (1995), soil amended with composted mango litter had higher mineral N in comparison with soil amended with untreated mango litter. Nitrogen immobilization/mineralization is generally slower in soils amended with more resistant compounds (Crippa and Zaccheo, 1995). Mango litter had a high C:N ratio (75.9) and composting reduced the C:N ratio and increased the N content of the litter, and the composted material may consequently have immobilized less N than fresh material.

Although all the three organic resources studied are poor and inadequate sources of N for plant growth in the short term, they may contribute to soil organic matter build-up in the long-term.

According to the organic resource data base developed by Palm et al. (2001), these materials should be mixed with fertiliser before application to soil in order to reduce the negative effects of N immobilisation, or added to compost in the case of miombo and mango litter.

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