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ORIGINAL ARTICLE

Nutrient release dynamics from decomposing organic materials and their mulching-effect on pearl millet yields in a low-input Sahelian cropping system

Ali Ibrahim · Robert Clement Abaidoo · Aboubacar Dan Kassoua Tawaye Iliasso · Dougbedji Fatondji

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Abstract Organic material inputs for increased crop yields are insufficient in the Sahelian West Africa. There is a need for diversifying organic amendment sources for improved nutrient supply in low-input cropping system. The 2-year study aimed to (1) explore the rates of mass losses and nutrient release dynamics from *Acacia tumida* prunings (AT) and millet straw (MS) under field conditions, (2) assess termite's contribution to the decomposition of AT and MS, and (3) ascertain the mulching-effect of these organic materials on pearl millet yields. The study was conducted in Niger using field experiment and litterbag methodology and the data modelled using single exponential decay equations. Under field conditions, mulching with AT and MS increased millet grain yield by 35 and 33%, respectively compared to control. The harvest index (HI) in 2014 increased by 21% compared to that obtained in 2013 with the highest HI being recorded for the AT mulched treatment. The results from litterbag experiment indicated a greater dry mass losses from MS decomposition in 2013 whereas relatively higher mass losses were recorded from AT decomposition in 2014. The differences in mass losses among the organic materials could be related to the interaction of soil moisture dynamics and termites' population which are positively correlated with mass losses. The contribution of termites to the decomposition was estimated to be 36% for MS and 8% for AT. In 2013, at 126 days after litterbags placement, the amounts of N, P, and K released from MS were 16, 1, and 25 kg ha^{-1} of initial nutrient applied, respectively compared with the 22, 1, and 23 kg ha^{-1} recorded from AT treatment. During the same period in 2014, the total amounts of N, P and K released from MS were 15, 0.6, and 29 kg ha^{-1}, respectively compared to the 32 kg ha^{-1} of N, 1 kg ha^{-1} of P, and 29 kg ha^{-1} of K released from the AT treatment. The intrinsic organic material quality could explain markedly the variation in nutrient released among the organic material. These results indicate that *Acacia tumida* prunings have a potential to provide nutrient through mineralization for enhanced crop yield in the Sahel.

Keywords *Acacia tumida* · Decomposition · Nutrient release · Soil fertility · Millet yield

A. Ibrahim (✉) · D. Fatondji
International Crops Research Institute for the Semi-Arid Tropics, BP 12404, Niamey, Niger
e-mail: ibabaye@gmail.com

Present Address:
A. Ibrahim · D. Fatondji
Office Chérifien de Phosphates (OCP Africa), Cotonou, Benin

R. C. Abaidoo · A. D. K. T. Iliasso
Department of Biological Sciences, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

R. C. Abaidoo
International Institute of Tropical Agriculture (IITA), PMB 5320, Ibadan, Nigeria

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Introduction

Crop production in the Sahelian regions is predominantly rainfed cereal-based cropping systems characterized by low productivity due to low soil fertility (Gandah et al. 2003). The lack of sufficient income limits the use of existing soil fertility recommendations by smallholder farmers, which consequently exacerbates the decline in soil fertility and decreases in crop yields (Chianu et al. 2012; Mapfumo 2011; Sanchez et al. 1997).

Organic resources are often promoted as alternatives to mineral fertilizers (Schlecht et al. 2006). However, the availability of organic materials for use as soil amendments on most farms is a daunting challenge. Smallholder farmers in the Sahel consider manure to be a basis for soil fertility management strategies but its use has generally been restricted to a few farmers endowed with livestock (Schlecht and Buerkert 2004). In the Sahel, crop residues such as millet (*Pennisetum glaucum* (L.) R.Br.), and sorghum (*Sorghum bicolor* (L.) straws are generally used for soil fertility maintenance and for the conservation of soil humidity because of their mulch effects. However, the accessibility to these residues in sufficient quantities is challenged by their competitive uses for animal grazing, fencing of houses and firewood (Bationo et al. 1998; Valbuena et al. 2015). For increased crop yields in low-input cropping systems, there is a need to diversify the sources of organic materials for soil fertility maintenance. This is particularly true for the Sahel where the farmland is generally characterized by the presence of few indigenous shrubs growing on farmers' fields (Schlecht et al. 2006) but vary in their mulch potential and effects.

The use of agroforestry trees for mulching in the Sahel could be a possible option to overcome the limited availability of organic amendments because of their capacity of providing large amounts of biomass in a relatively short period of time (Bayala et al. 2011). Recently, some agroforestry technologies have been developed in the Sahel. These include alley cropping systems in which trees such as *Acacia tumida* are intercropped with annual crops (Fatondji et al. 2011; Pasternak et al. 2005).

Acacia tumida, is one of coppicing trees introduced in the Sahel since 1980 with a primary aim of improving food security and combating hunger through the use of their seeds which are rich in protein and other nutrients (Rinaudo et al. 2002; Yates 2010). This species provides other benefits such as soil fertility improvement through nitrogen fixation and prunings for mulching (Rinaudo and Cunningham 2008). In a recent study, Ibrahim et al. (2015) showed that application of *Acacia tumida* prunings as mulch increased crop yield and water use efficiency. However, little is known about the potential of decomposition and nutrient mineralization from *Acacia tumida* prunings to improve pearl millet yield which is the main stable crop produced in the Sahel. The novelty of the present study is then in the identification of evidence to justify the importance of diversifying the sources of nutrients for soil fertility improvement in the biomass-scarce environment such as the Sahelian West Africa. Furthermore, the knowledge about nutrient mineralization and release from *Acacia tumida* prunings will enable smallholder farmers to manage nutrient release in a manner that optimises nutrient uptake and crop productivity. However, research has shown that the rates and patterns of decomposition and mineralization of an organic material incorporated into soil depends on the interaction between its quality and the prevailing soil biophysical factors including the community of the decomposers (Beare et al. 1992; Bending et al. 2004). It is generally, known that under dry conditions, the overall microbial activities are low (Coyne 1999). In a study conducted in the dry Sahelian conditions, Mando and Brussaard (1999) reported that termites significantly contributes to the breakdown of straw and therefore play a key role in nutrient recycling. There is therefore a need to establish whether the presence of termites has significant influence on the decomposition rate of *Acacia tumida* pruning. The objectives of this study were therefore to (1) explore the rates of mass losses and nutrient release dynamics from *Acacia tumida* prunings and millet straw under field conditions, (2) to assess termite's contribution to their decomposition rates and (3) to ascertain the mulching-effect of these organic materials on pearl millet yields.

Materials and methods

Description of the experimental site

The experiment was conducted in the 2013 and 2014 rainy seasons at the International Crops Research

Institute for the Semi-Arid Tropics (ICRISAT) Research Station which is located at Sadoré, Niger (13°15′N and 2°17′E, 240 m above sea level). This field experimental site had been left as fallow for 9 years. The soil of the experimental site, according to the FAO classification is a sandy Arenosol (West et al. 1984). The chemical and physical characteristics of the experimental field are presented in Table 1.The texture of the soil was sand, with 2.2 and 3.2% of silt and clay contents, respectively. Soil pH (H_2O) and pH (KCl) were 5.4 and 4.4, respectively. The organic carbon level was low (2.2 g kg^{-1}) while the nitrogen content of the soil was 195 mg kg^{-1}. The available P content and exchangeable bases were very low with 2.8 mg kg^{-1} and 19 $mmol_c$ kg^{-1}, respectively. The characteristics of this soil are representative of the soils in Niger which are characterized by sandy texture and low level of nutrients and organic matter.

The climate is characterized by a rainy season that takes place between June and September (4 months) followed by a long dry season which dominates the rest of the year. The rainfall distribution during the experiment period in 2013 and 2014 is illustrated in Fig. 1. The total rainfall recorded during 2013 cropping period was 481 mm, which was less than the long-term (1983–2014) rainfall average of 551 mm $year^{-1}$ at the experimental site (ICRISAT, climate database). In the 2014 rainy season, the total amount of rainfall recorded was 689 mm; and which was more evenly distributed compared to that of 2013.

Table 1 Initial soil properties of the experimental site (n = 16)

Parameters	0–0.2 m
Soil chemical properties	
pH-H_2O (1:2.5)	5.4 ± 0.0
pH-KCl (1:2.5)	4.4 ± 0.1
Organic C (g kg^{-1})	2.2 ± 0.0
Total-N (mg kg^{-1})	195 ± 10
Available P (mg kg^{-1})	2.8 ± 0.1
Exchangeable base ($mmol_c kg^{-1}$)	19 ± 1
Exchangeable acidity ($mmol_c kg^{-1}$)	0.3 ± 0.4
Soil texture (%)	
Sand	94.6 ± 0.1
Silt	2.2 ± 0.1
Clay	3.2 ± 0.2

± Standard error

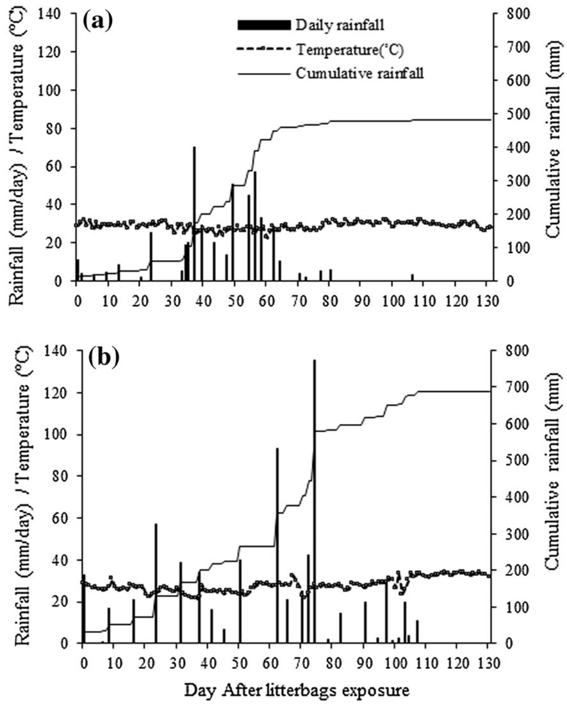

Fig. 1 Rainfall distribution and temperatures **a** in 2013 and **b** in 2014

The mean daily temperature during the study period were 29 and 28 °C, in 2013 and 2014, respectively (Fig. 1).

Experiments set-up

Details of field experiment

In order to assess the mulching-effect of MS and AT on pearl millet yields, a 2-year experiment consisting of three treatments: (1) *Acacia tumida* prunings, (2) millet straw application and a control (without organic mulch) arranged in randomized complete block design (RCBD) with three replications in both years was carried out. Each organic material was applied at a rate of 2000 kg ha^{-1} which is the recommended rate of crop residues application in the study area (Rebafka et al. 1994). The quantities of N, P, and K in the MS applied at 2000 kg ha^{-1} were 34, 2.6, and 26.8 kg ha^{-1}, respectively in 2013. In 2014, the N, P, and K quantities amounted to 16.8, 2, and 36 kg ha^{-1}, respectively. For AT, the amounts of nutrient applied were 40 kg N ha^{-1}, 2.4 kg P ha^{-1}, and 25.2 kg K ha^{-1} in 2013. In 2014, the quantities of nutrient applied were 45.2 kg N ha^{-1}, 2.8 kg P ha^{-1}, and 29.8 kg K ha^{-1}.

The size of each treatment plot was 7 m × 7 m. Seeds of an improved millet variety, ICMV IS 89305 (110 maturity days) were sown on 27th June 2013 and 1st June 2014 based on the onset of the rainy season. The planting holes were spaced at 1 m × 1 m to attain a planting density of 10,000 holes ha^{-1}. The millet plants were thinned to three plants per hole at 21 days after sowing followed by the first weeding. There were, three weeding events during each cropping year. The millet panicles, were harvested on 10th October in 2013 and 15th September in 2014 which coincided with millet maturity stage.

To determine millet grain yield and the total dry matter yield, straw samples and millet panicles were harvested from the central 5 m × 5 m portion of each plot and dried at 65 °C for 48 h. The harvest was then hand threshed and the dried samples were weighed and expressed in kg ha^{-1}. Harvest index (HI) was calculated as the ratio of millet grain yield to the total dry matter production.

Details of litterbag experiment

The litterbag experiments were conducted in the same fields and at the same time as the field experiment. The litterbags filled with MS and AT were randomly placed each year on the soil surface 1 week after millet was sown. Litterbags were also arranged in RCBD following the same experimental design used for the field experiment. MS and AT (leaves and stems with diameter < 10 mm) were collected from ICRISAT Research Station. For each organic material, fifty grams (50 g) of oven-dried material were put into a 200 mm × 200 mm litterbag made up of an iron net of 2 mm mesh size. A total of 12 litterbags for each material were placed in a replication.

In 2014, to estimate the contribution of termite on the decomposition of organic materials, additional litterbags (12 litterbags for each material) sprayed directly with the insecticide *fipronil*, were placed in a replication. The insecticide was applied each week directly on the litterbag at a rate of 0.002 m^3 ha^{-1} to control the presence of termites in the litterbags.

Litterbags were collected each year at 3, 6, 9, 12, 15 and 18 weeks after deposition (18 weeks corresponding to millet maturity stage). At each collection date, two litterbags for each treatment were randomly taken from each replication. The remaining organic material in the litterbag at each collection time was sun-dried, cleaned of adhered soil manually, and thereafter oven-dried at 65 °C for 48 h. The remaining oven-dried material was then weighed to calculate dry mass losses. To account for the weight of soil adhering to the organic material put into the litterbags, part of the remaining material from each treatment was burned at 550 °C in a muffle furnace to determine the ash weight. The true remaining organic material weight was determined using the method proposed by Kurzatkowski et al. (2004). The percentage mass loss of each organic material was calculated using the following formula:

$$\%\, Dry\ mass\ remaining = \frac{DW_t}{DW_i} \times 100 \quad (1)$$

where DW_t = Oven dry weight at time t, DW_i = Initial oven dry weight.

To calculate N, P, and K release at a specific litterbag collection time, the oven-dried organic material was ground and passed through 2 mm mesh sieve for N, P, and K analysis. The remaining mass for the two litterbags was mixed to make a composite sample. The composite samples were analyzed for total N, P, and K. Total N was analyzed by Kjeldahl method using a mixture of salicylic acid, H_2SO_4 and selenium for the digestion (Houba et al. 1995). The quantitative determination of total N was done with an auto-analyser using the colorimetric method based on the Bertholet reaction (Houba et al. 1995). The same digest was used for total P and K determination. Total P was quantified with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid and total K was determined with flame emission spectrophotometry (Houba et al. 1995).

It is noteworthy that before litterbags deposition in the field, the initial N, P, and K contents of each organic material were determined using the methods described above (Table 2). The polyphenol content was determined using the Folin-Denis method (Suzuki et al. 2002) and lignin was determined using Acid Detergent Fiber (ADF) method described by Van Soest (1963). The percent of nutrients remaining in the decomposing organic material at each sampling time was also determined by multiplying the remaining mass by the nutrient concentrations. In order to estimate the actual contribution of each organic

Table 2 Initial chemical characteristics of organic materials, $p < 0.05$

	Total N (g kg^{-1})		Total P (g kg^{-1})		Total K (g kg^{-1})		C/N ratio		Lignin (g kg^{-1})		Polyphenol (g kg^{-1})	
	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
MS	16.9 ± 0.4	8.4 ± 0.02	1.4 ± 0.05	1.0 ± 0.02	13.4 ± 0.03	18.2 ± 0.52	43.4 ± 9.1	64.0 ± 1.4	nd	77.3 ± 3.1	nd	6.3 ± 0.2
AT	20.0 ± 0.2	22.6 ± 1.8	1.3 ± 0.03	1.4 ± 0.00	12.6 ± 0.03	14.9 ± 0.01	19.7 ± 0.7	22.3 ± 0.7	nd	219.5 ± 21.1	nd	12.6 ± 0.7
Probability												
Year (Y)	0.238		0.553		< 0.001		0.010			nd		nd
Organic material (OM)	0.013		0.48		< 0.001		0.002			0.012		0.020
Y × OM	0.070		0.354		0.003		0.019			nd		nd
lsd												
Year (Y)	0.63		0.06		0.06		11.9			nd		nd
Organic material (OM)	0.63		0.06		0.06		11.9			6.90		0.39
Y × OM	0.9		0.09		0.09		16.8			nd		nd

MS millet straw, *AT Acacia tumida* prunings, ± standard error, *nd* not determined, *lsd* least significant differences of means material to crop's nutrient demand, nutrient release on quantity basis (kg nutrient per ha) was calculated by multiplying the percent released by the amount of litter applied.

The termite's population in litterbags was assessed according to the method developed by Tropical Soil Biology and Fertility (Anderson and Ingram 1993). The sampling was done with a metal frame measuring 150 × 100 × 100 mm directly under the place where the litterbag was deposited. The litterbags containing the organic material and the soil sample collected were transported to the laboratory to determine termite population by hand counting. The contribution of termites to the decomposition of organic material was calculated using the formula given by Mando and Brussaard (1999) as follows:

$$\textit{Termite contribution}\,(\%) = \left(\frac{A - B}{100 - B}\right) \times 100 \quad (2)$$

where A = percentage of organic material remaining in the litterbags without insecticide, B = percentage of organic material remaining in the litterbags with insecticide.

Soil sampling and analysis

Soil samples were taken at the onset of the experiment before the rainy season from 0 to 0.2 m from each plot. Each sample was analysed for pH (H_2O) using pH meter (with a 1:2.5 soil: water ratio), organic carbon was determined using the method described by Walkley and Black (1934); and total nitrogen (N) was determined using Kjeldahl method (Houba et al. 1995). Available phosphorus was determined using the Bray-1 method as described by van Reeuwijk (1993). The quantitative total N was determined with an auto-analyser using the colorimetric method based on the Bertholet reaction (Houba et al. 1995). Exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}) were extracted by the ammonium acetate (NH_4OAc) solution at pH 7 using the extraction method described by van Reeuwijk (1993). The particle size distribution was determined using pipette method (Gee and Or 2002).

Measurement of soil moisture

Soil moisture content was measured weekly with a neutron probe (Didcot Instrument Company Limited, Station Road Abingdon, Oxon OX143 LD) and a 2-m long access tube installed in each experimental plot. The measurements were taken at 0.15 m interval in all the plots. Before the measurements, the neutron probe was calibrated in-situ for the soil of the experimental field using the gravimetric method as described by the manufacturer. The data collected with the neutron probe were used to calculate the volumetric soil water content (VWC) using the formula used by Fatondji (2002) as follows:

$$\theta v = a + b\left(\frac{C}{Cs}\right) \quad (3)$$

where θ_v is volumetric water content (VWC) expressed in %; a is the intercept, and b represents the slope of the equation ($y = 49.081 + 1.4961x$) resulted from the neutron probe calibration curve. From this equation, y is volumetric soil water content; x is the relative count ratio (it is the ratio of the neuron probe reading in the field (C) to the standard count reading from the access tube installed in pure water (Cs).

Data processing and analysis

Prior to the analysis, the data were checked for normality and homogeneity of variance using analysis of variance (ANOVA) residual plot options in GenStat (General Statistics). Thereafter, data were subjected to ANOVA using a General Treatment Structure (in Randomized Blocks) in GENSTAT v.9 (GenStat 2007). When necessary, mean separations were performed using the least significant difference (LSD) test at an error probability < 0.05. Organic material decomposition and nutrient release data were analyzed statistically based on repeated measures using the AREPMEASURES procedure in GENSTAT v.9. The single exponential decay model described by Wider and Lang (1982) was used to determine decomposition and nutrient release rates constants (k) as follows:

$$C_t = C_0 e^{kt} \quad (4)$$

Table 3 Millet grain yield and total dry matter yields, $p < 0.05$

Treatments	Grain yield (kg ha^{-1})		Total dry matter yield (kg ha^{-1})		Harvest index (%)	
	2013	2014	2013	2014	2013	2014
MS	570 ± 61	1107 ± 213	2433 ± 309	3513 ± 471	24 ± 2	30 ± 2
AT	597 ± 65	1117 ± 69	3212 ± 529	3688 ± 265	19 ± 2	31 ± 1
Control	402 ± 17	695 ± 99	1605 ± 56	3165 ± 188	25 ± 2	21 ± 3
Probability (p)						
Year (Y)	< 0.001		0.008		0.023	
Organic material (OM)	0.016		0.059		0.19	
Y × OM	0.332		0.406		0.013	
CV (%)	24.6		22.8		14.8	

MS millet straw, *AT Acacia tumida* prunings, *CV* coefficient of variation, ± standard error

where C_0 is the percentage of initial organic material or initial nutrient content and C_t is the percentage of the initial nutrients remaining at time t, t = time (days), and k (days^{-1}) the decay constant. In the formula, C_0 was set to 100% and k was fitted from the observed data using GenStat v.9. It should be noted that k-values and release rates have been calculated on annually application rates basis. ANOVA was carried out on decay constant (k) values in GenStat v. 9 (GenStat 2007). Differences for all the analysis were reported as significant if the probability was less than 5%.

Results

Characteristics of organic materials

In 2013, the N contents of MS and AT did not significantly differ from that of 2014 (Table 2). However, there was, a significant difference in N content between MS and AT treatments. The initial N contents of AT of 20 g kg^{-1} in 2013; and 23 g kg^{-1} in 2014 were significantly higher than those of MS for both years (Table 2). The C/N ratio significantly differed between the organic materials with the highest C/N ratio of 43 in 2013 and 64 in 2014 recorded for MS (Table 2). There was a significant interaction between C/N ratio of organic material and experimental year. The C/N ratio was significantly lower for AT in both years. The initial P content for MS was 1.4 g kg^{-1} in 2013 and 1.0 g kg^{-1}in 2014; which did not significantly differ from the 1.3 and 1.4 g kg^{-1} recorded for AT in 2013 and 2014, respectively. However, the K contents of 13.4 g kg^{-1} in 2013 and 18.2 g kg^{-1} in 2014 were higher for MS than the 12.6 and 14.9 g kg^{-1} recorded for AT in 2013 and 2014 respectively (Table 2). Lignin and polyphenol contents were both significantly higher for AT compared to those recorded for MS (Table 2).

Millet yields and harvest index

Millet grain and total dry matter yields obtained in 2014 were significantly higher than those recorded in 2013. Mulching increased millet grain significantly (Table 3). Application of AT increased millet yield by 32% in 2013 and 38% in 2014, in relation to those of the control treatments (without mulch). Addition of MS mulch led to an increase in millet grain yield by 29% in 2013 and 37% in 2014 compared to that of control plots. However, grain yields in the plots mulched with AT did not differ significantly from those obtained in MS mulch. There were no significant differences in total millet dry matter production recorded for organic mulching materials in both years (Table 3) even though total dry matter yields were relatively higher in AT mulched plots. No significant interactions were observed between year and organic mulches with regard to millet grain and total dry matter production.

The harvest index (HI) of millet in 2014 season was 21% higher than that recorded in 2013 but there were no significant variations in HI of the two mulching treatments (Table 3). However, there was, a significant interaction between mulch treatment and cropping year. In 2013, the harvest index was generally greater for plots that did not receive any mulch. In 2014, the increase in the HI compared to control plots was 42 and 48% for MS and AT, respectively.

Organic material mass losses and termites contribution

The results revealed significant interactions between year and organic materials for mass losses (Tables 4, 5). Generally, the highest mass loss of 75% was recorded for MS in 2013 (Fig. 2a). However, in 2014, the decrease of 67% for AT was higher compared to the 55% of MS (Fig. 2b).

The decay constants (*k*) for mass losses significantly differed with experimental year (Table 4). The *k* values recorded in 2013 were significantly higher than those recorded in 2014 irrespective of the organic material used. There was a significant interaction between year and organic material on decay constants. Generally, mass losses of MS in 2013 were faster as indicated by the greater *k* value for MS than for AT (Table 4). However, in 2014, mass losses for AT tended to be more rapid as evidenced by the relatively larger *k* value recorded (Table 4).

Termites' population was significantly higher in litterbag containing millet straw (Table 6). Termite contributed markedly to the decomposition of MS with 36% of material decomposed potentially attributed to termite activities while only 8% of AT were attributed to termites (Table 6). There was, a strong and significant correlation (r = 0.92) between MS mass losses and termites' population whereas a moderate relationship (r = 0.49) between AT mass losses and termite population was noted (Table 7).

Nitrogen, phosphorus and potassium release from decomposing organic materials

The rate of nitrogen release from AT was significantly more rapid as shown by the higher *k* values recorded for this organic material (Table 4). The decay constant (*k*) values for N release differed markedly between experimental years irrespective of organic materials. The rate of N release from AT was significantly faster in 2014 than in 2013. There was a significant interaction between organic materials and experimental year for N release (Table 5). In 2013, the quantities of N released from MS averaged 10 kg N ha^{-1}

Table 4 Effect of organic material on dry mass losses and nutrient decay constant (*k*) $days^{-1}$, $p < 0.05$

	Mass loss		N		P		K	
	2013	2014	2013	2014	2013	2014	2013	2014
MS	0.015 ± 0.000	0.006 ± 0.000	0.004 ± 0.000	0.014 ± 0.001	0.005 ± 0.000	0.004 ± 0.000	0.040 ± 0.004	0.017 ± 0.000
AT	0.012 ± 0.001	0.008 ± 0.000	0.006 ± 0.000	0.017 ± 0.000	0.005 ± 0.001	0.005 ± 0.000	0.021 ± 0.000	0.019 ± 0.000
Probability (p)								
Year (Y)	< 0.001		< 0.001		0.736		< 0.001	
Organic material (OM)	0.785		0.029		0.058		0.006	
Y × OM	0.005		0.045		0.736		0.002	

MS millet straw, *AT Acacia tumida* prunings, ± standard error

Table 5 Summary of analysis of variance showing *p* values on mass losses, nutrient (N, P and K) release from decomposing organic materials and volumetric water content (VWC)

Source de variation	Mass loss	N	P	K	VWC
Year (Y)	< 0.001	< 0.001	< 0.001	0.948	< 0.001
Organic material (OM)	0.016	< 0.001	0.465	< 0.001	0.115
Time (T)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Y × OM	< 0.001	< 0.001	< 0.001	0.413	0.507
Y × T	0.038	0.021	< 0.001	< 0.001	< 0.001
OM × T	0.292	< 0.001	0.003	0.006	0.613
Y × OM × T	0.46	< 0.001	0.852	< 0.001	0.318

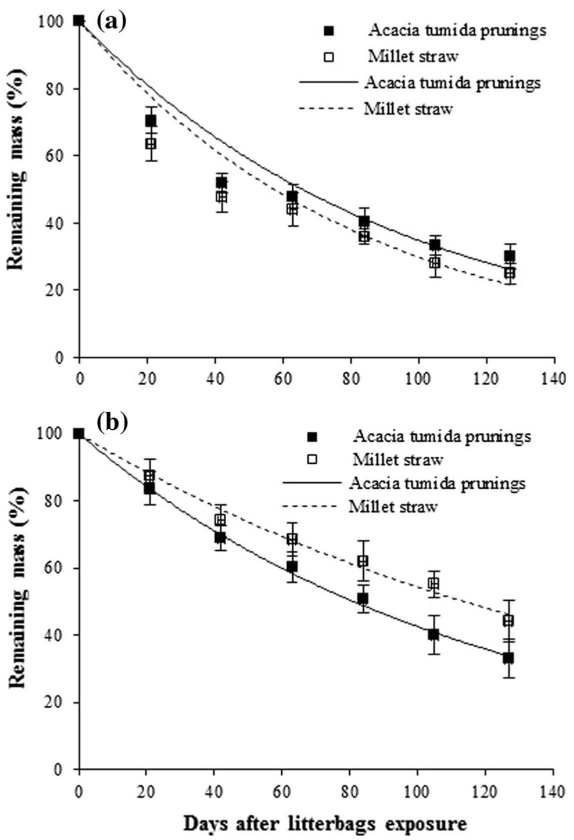

Fig. 2 Mass loss from millet straw (MS) and *Acacia tumida* prunings (AT): **a** in 2013 and **b** in 2014

(Fig. 3a) and which accounted for 29% of its initial N content compared to 16 kg N ha^{-1} for AT (or 40% of the initial N content). Conversely, in 2014, the quantities of N released from MS averaged 11 kg N ha^{-1} (32% of initial N content) compared to 28 kg N ha^{-1} (70% of initial N content) for AT (Fig. 3d). In 2013, the highest N (16 kg N ha^{-1}) release, representing 47% of initial N content of MS, occurred at 126 days after litterbags placement compared to the 22 kg N ha^{-1} (or 55% of initial N content) that was released from AT. In 2014, at the same sampling time, the amounts of N released were 15 kg N ha^{-1} (89% of initial N content) and 32 kg N ha^{-1} (71% of initial N content), for MS and AT, respectively (Fig. 3d).

The rate of P decay did not significantly differ among the organic materials (Table 4). The interaction of organic material and experimental year was also not significant. Similarly, the quantity of P release did not significantly differ among the organic materials (Table 5). However, there was a significant interaction between experimental year and organic material in the quantity P released (Table 5). In 2013, the quantity of P released from MS, was on average 1.3 kg P ha^{-1} (50% of initial P content) compared to the 1.1 kg P ha^{-1} (45% of initial content) recorded for AT (Fig. 3b). In 2014, the average P released from MS was 0.6 kg P ha^{-1} (32% of initial P content) compared to the 0.9 kg P ha^{-1} (32% of initial P content) released from AT (Fig. 3e). At 126 days after litterbags placement, P released from MS and AT in 2013 was approximately 1 kg P ha^{-1} but accounted for 39 and 41% of the initial P contents of MS and AT, respectively (Fig. 3b). In 2014, at the same period, the amounts of P released were 0.6 kg P ha^{-1} (30% of initial P content) for MS and 1 kg P ha^{-1} (35% of initial P content), for AT (Fig. 3e). The P released varied significantly with litterbag collection time. In general, the quantity of P released was greater from 20 to 60 days after litterbags placement and decreased in all the materials from 80 to 126 days after litterbags placement (Fig. 3b, e).

Potassium (K) appeared to be the nutrient with the fastest release rate as compared to N and P. The differences between the decay constant values (k) for K of the organic materials were significant (Table 4). There was also a significant interaction between organic material and experimental year in K decomposition coefficients. The K release was markedly more rapid in 2013 as evidenced by greater decay constants obtained particularly for MS (Table 4). However, no significant interaction was detected between organic material and experimental year on the quantity of K release (Table 5). In 2013, the average amount of K released for MS was 21 kg ha^{-1}, (82% of initial K content) compared to the 19 kg K ha^{-1} (74% of initial K content) for AT (Fig. 3c). In 2014, K released averaged 18 kg K ha^{-1}, (51% of initial K content) for MS compared to the 19 kg K ha^{-1} (63% of initial K content) for AT (Fig. 3f). At 126 days after litterbags placement, K released in 2013 was 25 kg K ha^{-1} for MS and 23 kg K ha^{-1} for AT which represented 93 and 91%, of its initial K contents, respectively (Fig. 3c). In 2014, at the same sampling time, the quantity of K released amounted to 29 kg K ha^{-1} for both organic materials which accounted for 81 and 97% of initial K contents for MS and AT, respectively (Fig. 3f).

Table 6 Termites' population and termite contribution to organic material, $p < 0.05$

Organic material	Termite number	% Termite contribution
MS	$103^{a} \pm 16$	$36^{a} \pm 6$
AT	$5^{b} \pm 2$	$8^{b} \pm 2$
Probability (p)	0.003	0.026
lsd	38	26

MS millet straw, *AT Acacia tumida* prunings

Soil moisture content as affected by organic material mulches

Soil volumetric water content (VWC) in the top 0.15 m soil depth is illustrated in Fig. 4, and summary of analysis of variance is presented in Table 5. There were no significant differences in VWC among the treatments. Yet, the soil under AT was generally more moist and the lowest soil volumetric water content was recorded under control plots. There was a significant year effect on VWC with the greater soil water content recorded in 2014.

Table 7 Pearson correlation coefficients between observed variables

MS						
Mass loss	1					
Termite pop.	0.923**	1				
N release	− 0.804*	0.557	1			
P release	− 0.546	0.636	0.319	1		
K release	− 0.921**	0.829*	0.802	0.748	1	
VWC	0.510	0.892*	0.821*	0.686	0.955**	1
AT	**Mass loss**	**Termite pop.**	**N release**	**P release**	**K release**	**VWC**
Mass loss	1					
Termite pop	0.493	1				
N release	− 0.643	0.162	1			
P release	− 0.748	− 0.228	0.681	1		
K release	− 0.969**	− 0.579	0.601	0.842*	1	
VWC	0.637	− 0.172	0.877*	0.598	0.658	1

Termite pop. termite population

**Correlation is significant at the 0.01 level

*Correlation is significant at the 0.05 level

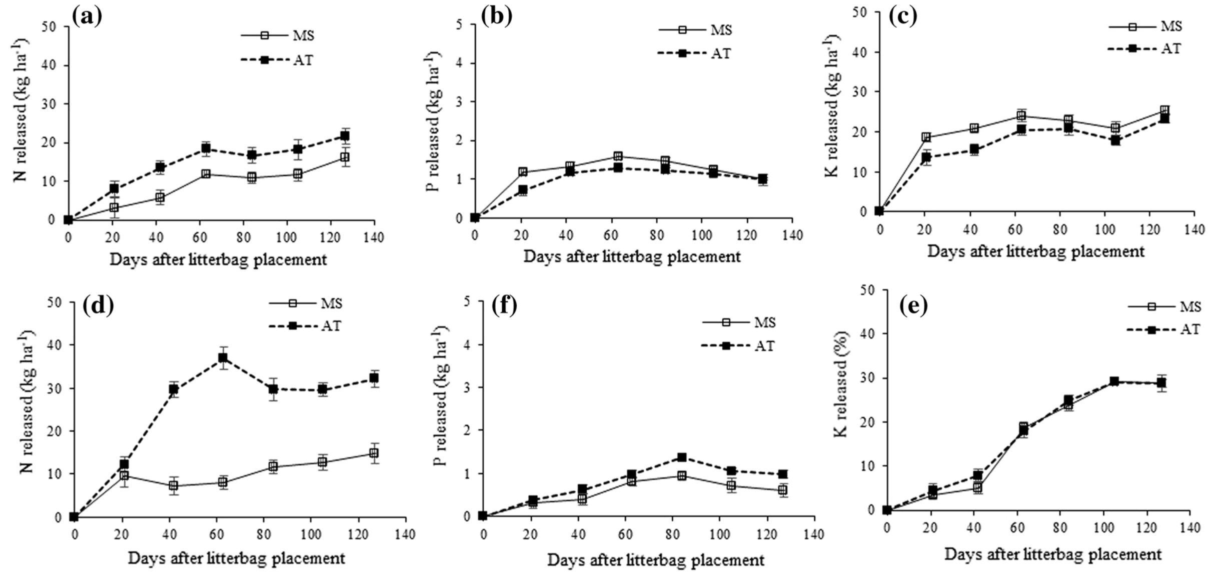

Fig. 3 N, P, and K released from millet straw (MS) and *Acacia tumida* prunings (AT). Error bars represent standard errors of the mean. Top figures represent nutrient remaining in 2013 and bottom figures represent nutrient remaining in 2014

Discussion

Millet yields and harvest index

Millet grain yields increased significantly with organic mulch application. The increase in millet yield recorded under mulched plots could be attributed to the improvement in soil moisture condition particularly in the plots mulched with AT (Ibrahim et al. 2015). Adequate soil moisture content encourages better crop growth and thereby enhances crop yields particularly in dry spell-prone areas. There was a significant seasonal difference in millet grain yield and total dry matter yields. This seasonal yield variability could be attributed to the larger amount and better rainfall distribution observed throughout the growing period in 2014 (Fig. 1). Another possible reason for the yield variability might be due to the residual effect of 2013 mulching activity and the possible augmentation of the 2014 mulching resulting in enhanced nutrients supply to millet crop. The harvest indices (HI) recorded were low, but not uncommon for pearl millet grown in the Sahel (de Rouw 2004; Manyame 2006).

Organic material quality

The decomposition of an organic material is known to be controlled by its chemical characteristics and interactions with environment and decomposer community. Among the chemical characteristics of an organic material, N content and C/N ratio exert a great influence on its decomposition rate (Palm and Sanchez 1991). The initial N, P, and K concentrations for MS in the current study were much higher than those reported by Fatondji et al. (2009) in Niger. In general, the chemical composition of AT was within the range of agroforestry prunings used in the Sahel (Bayala et al. 2005; Ouédraogo et al. 2004). Considering the threshold of 25 g N kg^{-1} as the determinant of N mineralization, and C/N ratio of 20–25 above which N would be immobilized, MS used in the current study is of low quality (Palm et al. 2001; Sileshi et al. 2016). Accordingly, AT with relatively high N content and lower C/N ratio would be much easier to be mineralised by the decomposer community.

Organic material mass losses and termites contribution

Contrary to expectations, a greater mass loss was recorded with millet straw in 2013 although the quality

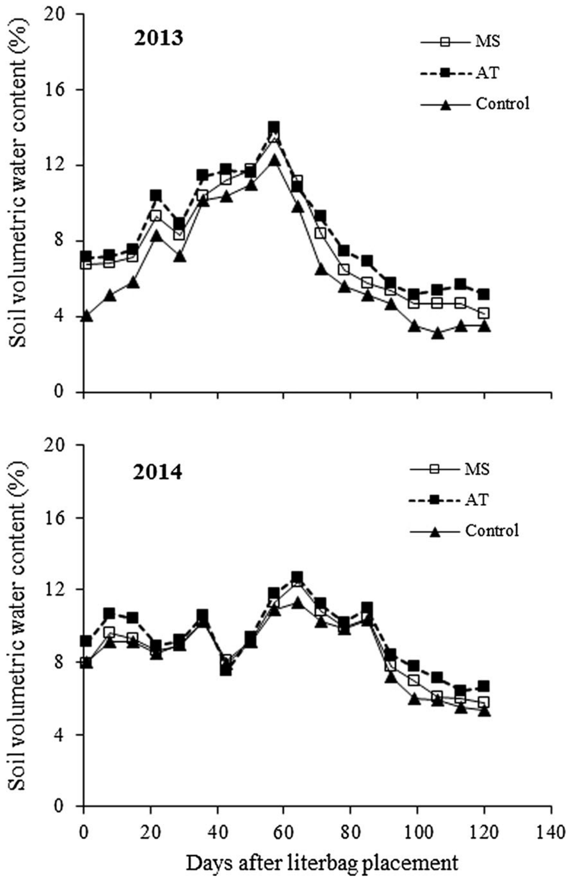

Fig. 4 Soil volumetric water at soil depth 0–0.15 m as affected by organic materials

of this organic material was relatively low. This result supports the finding of previous study by Tian et al. (2007) who reported the possibility of residues of low N content and high C/N ratio to decompose faster in the dry areas than high quality residues. In arid environment, a large decomposition rate of low quality organic material is generally attributed to the contribution of soil fauna and photo-degradation which alter the control of organic material quality in the decomposition process (Bending et al. 2002; Tian et al. 1993). Nevertheless, in 2014 the higher mass losses were documented for AT which had a lowest C/N ratio of 22 and relatively higher initial N content. This finding is consistent with that of Sanchez (2001) who showed that an organic material of high quality (characterized by higher N concentration and lower C/N ratio) could decompose faster compared to low quality organic material. This is especially the case when moisture conditions allow optimum activity of microorganisms responsible for organic material decomposition. There was a year-effect on the decomposition of organic materials. Mass loss in both organic materials was higher in 2013 as compared to 2014. Several studies, have reported seasonal differences in the decomposition of applied organic material in West African semi-arid environments (Fatondji et al. 2009; Gonda et al. 2016; Tian et al. 2007). The seasonal differences are generally attributed to soil moisture variability which regulates microbial activity. Even though, soil moisture was correlated with mass losses as evidenced by the relatively high correlation coefficients (Table 7), the decrease in mass losses during the wet year (2014) attested that other factors could influence the decomposition of these organic materials. The results of this study showed a strong and significant correlation between mass loss and the termite's population particularly for MS suggesting a substantial contribution of termites in the degradation of this organic material (Table 6). The presence of termites enhances comminution of low quality material and thereby making the substrate better accessible to microorganisms and facilitating its decomposition process (Tian et al. 2007). The highest contribution of termites to millet straw decomposition is consistent with results of previous studies which have shown large mass losses of low quality organic resource when termites are present (Mando and Brussaard 1999; Ouédraogo et al. 2004; Tian et al. 1995). However, Higashi et al. (1992) showed that termites in general nourish on dead plant material which has a C/N ratio relatively higher than their own tissues in order to balance their carbon and nitrogen inputs. An earlier study, reported C/N ratio of 4 to 12 for termite tissues (Matsumoto 1976). The C/N ratios of the organic materials used in this study were markedly greater than those of termites' tissues which indicates that all these materials were attractive to the termites. If the hypothesis of Higashi et al. (1992) has to be held true, the lower termites' population observed on AT seems to be unclear because of the higher C/N ratio (22) of this material compared to C/N ratio of termites tissues. Nevertheless, Mando and Brussaard (1999) reported that the dominant termite species in the Sahel is *Macro-termitinae*, and they are less affected by the quality of their food because of their symbiotic relationship with *Basidiomycete* fungi. It seems, therefore, possible that the limited number of termites on AT (Table 6) resulted from the foraging behaviour of termites which favoured the preference of MS over AT.

Nutrient release

Nitrogen released from MS was relatively lower in 2013 compared to that from AT (Fig. 3). The trend of N release did not reflect the pattern of disappearance of millet straw mass in 2013 (Fig. 2). The current result indicates that the disappearance of an organic material from the litterbags does not necessarily imply that there was an absolute mineralisation of the removed portion. The losses in mass of MS recorded in 2013 could be attributed to the presence of soil faunal populations particularly termites which would facilitate the decomposition of this organic material. Generally, the rate of release and quantity of N released from AT was more rapid and higher in both years compared to that of MS. This supports the findings of earlier studies (Gnankambary 2007; Munthali et al. 2015) that reported the highest amount of N released from an organic material with high quality (high initial N content, low C/N ratio) represented by AT in the current study. Additionally, the large quantity of N released from AT in 2014 could rather be attributed to the relatively good rainfall distribution which improved soil moisture content. The quantity of N released was significantly correlated with soil moisture content (Table 7). The improved soil moisture conditions may have induced an increase in the soil microbial activity and thereby enhanced N release.

The amount of P released from the decomposing material was mostly higher in MS compared to that recorded for AT particularly in 2013. The relatively higher P released from MS could be explained by the proportion of P initially present in MS compared to that of AT. Kwabiah et al. (2003), reported that P release during decomposition was positively correlated with the initial P content. On the other hand, P release from the organic materials was higher from 20 to 60 days after litterbags placement and decreased in all the materials from 80 days to the end of the experiment. This could be explained by the changes in soil moisture dynamics as evidenced by the positive correlation observed between VWC and P release (Table 7). A decrease in soil moisture content may have induced a reduction of soil microbial activities responsible for P mineralization (Kabba and Aulakh 2004).

The K release was more rapid than N and P release. The rapid K release from organic materials is frequently reported during mineralization and this is related mainly to higher water solubility of this nutrient compared to N and P (Bayala et al. 2005; Esse et al. 2001; Teklay 2007).

Earlier research has shown that 30 kg N ha^{-1}, 13 kg P ha^{-1} and 25 kg K ha^{-1} would be needed for enhanced millet production and maintained soil fertility in Niger (Hayashi et al. 2008). Our results however suggest that the quantities of nutrient released, particularly P and to some extent N from AT applied at a rate of 2000 kg ha^{-1} are not sufficient to satisfy millet nutrients requirement for optimum yield production during the cropping season. Thus, the current application rate of AT prunings would be revisited in order to avoid the depletion of native soil nutrients, especially P which is markedly limited in *Acacia tumida* prunings.

Conclusion and recommendation

The results of this study indicate that AT and millet straw can be considered as decomposable mulches with the potential of providing nutrient for enhanced pearl millet yield. The contribution of termites to the decomposition of AT is small as a result of the foraging behaviour of termites which favours the preference for MS. Since, the nutrient released from the applied rate of AT could not adequately support the recommended rate of nutrient for increasing millet production and maintaining soil fertility, we recommend that the current application rate should be increased or supplemented with other sources of soil nutrient for improving further millet yield and sustaining soil fertility.

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