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ORIGINAL ARTICLE

# Improving nutrient use efficiency from decomposing manure and millet yield under Plinthosols in Niger

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**Abstract** To improve synchronicity between nutrients released from the decomposing manure with millet nutrient requirement under zaï technique, a 2-year field experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics Research Station, Sadoré, Niger. The treatments consisted of factorial combination of two rates of cattle manure (200 and 300 g per zaï hole), three periods of manure application (before planting, at planting and 15 days later) and two rates of mineral fertilizer [nitrogen (N), phosphorus (P) and potassium (K) 15–15–15] applied at 6 g per zaï hole and a control, without mineral fertilizer). Manure dry mass losses did not significantly differ among manure application periods in 2013. However, in 2014 the highest manure dry mass loss occurred when manure was applied before planting with 70% of manure applied being decomposed at millet maturity stage (115 days after litterbag installation) followed by manure applied at planting with almost 50% of dry mass losses. The quantities of N and P absorbed by millet at tillering stage represented, 61, 52 and 33% of N released and 15, 12 and 15% of P released at the same time when manure was applied before planting, at planting and 15 days after planting, respectively. Application of manure before planting increased on an average millet grain yield by 16 and 20% and N utilization efficiency by 25 and 31% compared to application of manure at planting and 15 days after planting respectively. Addition of mineral fertilizer induced a synergetic effect on millet grain yield ($p = 0.002$). Millet grain yields increased on average by 5, 17 and 57% when 6 g per zaï pit of NPK fertilizer were added to plots receiving manure application before planting, at planting and 15 days after planting, respectively. We conclude that application of manure prior to planting satisfies better millet nutrients demand, thereby increasing nutrient use efficiency and grain yield under zai pits.

**Keywords** Degraded soil · Manure · Nutrient release · Nutrient uptake · Synchronicity · Millet

## Introduction

Land degradation due to soil erosion and inherently low soil fertility coupled with poor soil fertility management practices are the major factors affecting crop production in most sub-Saharan African countries (Zingore et al. 2015). In the Sahel, crop production is predominantly rainfed cereal-based and characterized by low yields as a result of unpredictable rainfall and continual decline in soil fertility

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(Gandah et al. 2003; Voortman 2010). Pasternak et al. (2009) reported that more than 50% of the Sahelian soils are degraded and most of these degraded soils are crusted lateritic soils which undergo a continuous process of erosion, mostly by wind but also by water. Thus, the limited land resource is shrinking slowly while population increases with ever increasing demand for food. For improved crop production to feed the growing population in the Sahel, there is, a need of rehabilitating the productive capacity of these degraded soils. Thus, farmers have developed water harvesting-based technologies to bring back into production the degraded lands in the Sahel (Roose et al. 1999).

Zaï technique which consists of digging small basins of variable size usually 20–40 cm in diameter and 10–20 cm deep to collect runoff water is the most common water harvesting techniques used to rehabilitate the degraded soils in the Sahel (Roose et al. 1993). In Burkina Faso, the development of zaï pits, has led to an expansion of farms size with associated crop yield increment (Kaboré and Reij 2004). In Niger, Fatondji et al. (2006), reported that zaï improved millet water use efficiency by a factor of about 2 and improved nutrient uptake in the range of 43–64% for N, 50–87% for P and 58–66% for K. This technique has been advocated to improve nutrient and water use efficiency thereby increasing crop yield in short time while restoring lands in long term (Lahmar et al. 2012). However, to acquire the beneficial effects of zaï, the application of organic amendment remains essential. A field experiment conducted in Burkina Faso, to examine the effect on soil productivity of soil and water conservation technique in association with different sources of nutrients revealed that, restoring favourable soil moisture condition without addition of crop fertilizing elements could not improve crop yields under encrusted soil conditions (Zougmoré et al. 2003).

Traditionally, animal manure plays an important role in maintaining soil fertility of the Sahelian smallholder farming systems. Manure is a source of soil nutrients and is beneficial to soil physical properties (Harris 2002). Many studies, have shown that manure application in the zaï pits increases crop yields, augments soil organic matter content, ameliorates soil pH, improve soil nutrients and soil moisture status (Boubacar et al. 2016; Bouzou and Dan Lamso 2004; Fatondji et al. 2006; Wildemeersch et al. 2015). In Niger, manure application in zaï pits resulted in 2–68 times higher grain yields than in no amended zaï pits (Fatondji et al. 2006). In another study conducted in Niger, Bouzou and Dan Lamso (2004), observed significant increase in millet grain yield when organic amendment was applied under zaï pits. In Burkina Faso, application of manure under zaï pits increased nutrient uptake by 43–87% and yield by 35–220% (Ouattara et al. 1999). In another study, Fatondji et al. (2009) observed that organic amendment decomposition was slower under zaï pits compared to surface application of organic material due to the presence of termites. In the same study, the authors have reported a poor synchrony between nutrients release and pearl millet nutrient uptake. The poor synchronicity could increase the risk of nutrients losses by leaching particularly for nitrogen (N). It appears that inappropriate manure management under zaï technique can greatly reduce its efficiency and may affect crop yields. There is, therefore a need to enhance the efficient use of manure under zaï technique by matching nutrients release from decomposing manure with crop nutrient demand for improving crop yields particularly in the Sahel characterized by limited availability of organic amendments at many places (Schlecht et al. 2006).

Earlier report by Mafongoya et al. (1998) showed that, one of the strategies to improve the efficient use of nutrient from decomposing organic amendment, is through regulating the rates of nutrients release to improve the synchronicity of nutrient supply with crop demand. According to Gascho et al. (1995), this depends on yield target and the rate of nutrients applied. For instance, the latter authors, have observed that with final grain yield of 2229 kg ha$^{-1}$ following the application of 45 kg N ha$^{-1}$, nitrogen (N) content at panicle emergence was 2.46% in the leaves. For grain yield of 1497 kg ha$^{-1}$ and the same rate of N application, N content at the stage of flag leave was 1.64 and 2.76% at panicle emergence. Accordingly, manipulating manure application schedule may ensure the availability of the nutrients to the plant at right time.

Variation in manure application period can also avoid large nutrient losses by leaching that may occur, especially for N in zaï pits. The study on synchronicity between nutrients released from decomposing manure under zaï technique with pearl millet nutrients requirement has not yet been investigated. The objective of the present study was to determine the optimal time of manure application under zaï technique for enhanced synchronicity between nutrient releases from decomposing manure with pearl millet nutrient requirement.

## Materials and method

### Experimental site

The experiments were conducted in the 2013 and 2014 rainy seasons on the Bio-reclamation of degraded land (BDL) experimental site of International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) located at Sadoré village, Niger (13°15′N and 2°18′E, 240 m above sea level). The BDL site, is a degraded bare land fenced, and treated with soil and water conservation structures (zai pits and half-moons) for its biological rehabilitation. The soil is classified as Plinthosols in the FAO classification system. The climatic conditions, are similar to that of the ICRISAT Research Station and characterized by a rainy season that takes place between June and September. A dry season, dominates the rest of the year. The rainfall distribution and temperatures during the experiment period in 2013 and 2014 are illustrated in Fig. 1. The total rainfall recorded from planting to crop harvest in 2013 was 481 mm. In 2014, rainfall was evenly distributed with 689 mm recorded from planting to crop harvest. Minimum and maximum temperatures during the same period were 21.0 and 34.2 °C, respectively in 2013. In 2014, minimum and maximum temperatures were 21.6 and 34.9 °C, respectively.

The initial physical and chemical characteristics of the experimental field within the top 20 cm are presented in Table 1. Soil pH ($H_2O$) and pH (KCl) were 4.5 and 4.0, respectively. The organic carbon level, was low (0.34%). The nitrogen content of the soil was low (272 mg $kg^{-1}$). The available P content and exchangeable bases were very low with 6.4 mg $kg^{-1}$ and 0.9 $cmol_c$ $kg^{-1}$, respectively.

### Experimental design and crop management

During the dry season (in May), zaï planting holes of 20 cm diameter and 20 cm deep were dug with a spacing of 80 cm × 80 cm in the experimental field. Individual plot size was 8 m × 8 m. The experiment was designed as a 2 × 2 × 3 factorial experiment organized in a randomized complete block design with four replications. The treatments consisted of a factorial combination of : (1) two rates of mineral fertilizer (NPK 15–15–15) applied at 6 g per zaï hole and a control, without mineral fertilizer), (2) two rates of cattle manure (200 and 300 g per zaï hole corresponding to 3125 and 4688 kg $ha^{-1}$ of manure, respectively) and (3) three periods of manure application (before planting (34 and 24 days before sowing in 2013 and 2014, respectively), at planting and 15 days after planting). Date of manure applied before planting varied between years due to uncertainties in the start of the rainy season which determines the day of planting.

The application of 6 g per zaï hole of NPK, is the current fertilizer micro-dosing rate recommended in Niger (Tabo et al. 2011). The rate of 300 g per zaï hole of manure applied was the optimal application rate suggested by Fatondji et al. (2006) and considering the limitation of manure availability in the study area, a moderate rate of 200 g per zaï hole was also tested. The manure application periods, were chosen based on the study by Fatondji et al. (2009) who have observed that, inappropriate timing application of manure resulted in decomposition trend that leads to a poor synchrony between nutrient release and crop nutrients requirement. Cattle manure applied was collected from the country side of Niamey, the capital city in pile of waste of animal dejection and crop residues. NPK 15–15–15 fertilizer (94 kg $ha^{-1}$ equivalent to 14.1 kg N $ha^{-1}$, 6.3 kg P $ha^{-1}$, and 11.7 kg K $ha^{-1}$) was applied at millet sowing date.

Seeds of millet variety, ICMV IS 89305 (110 maturity days) were sown on 2th July, 2013 and 27th June, 2014 based on the onset of the rainy season. Two weeks after planting, plants were thinned and 2 plants per zaï hole were left till harvest. There were, two weeding events during each cropping season.

### Data collection and calculations

The millet panicles, were harvested at maturity stage. Millet maturity stage when the last litterbag sampling was done, corresponded to 134, 100 and 85 days of manure placement for litterbags installation in the zaï pits before planting, at planting and 15 days after planting respectively in 2013. For experimental year 2014, millet maturity stage at which the last litterbag sampling was done, coincided to 115, 91 and 71 days of manure placement for litterbags installed before

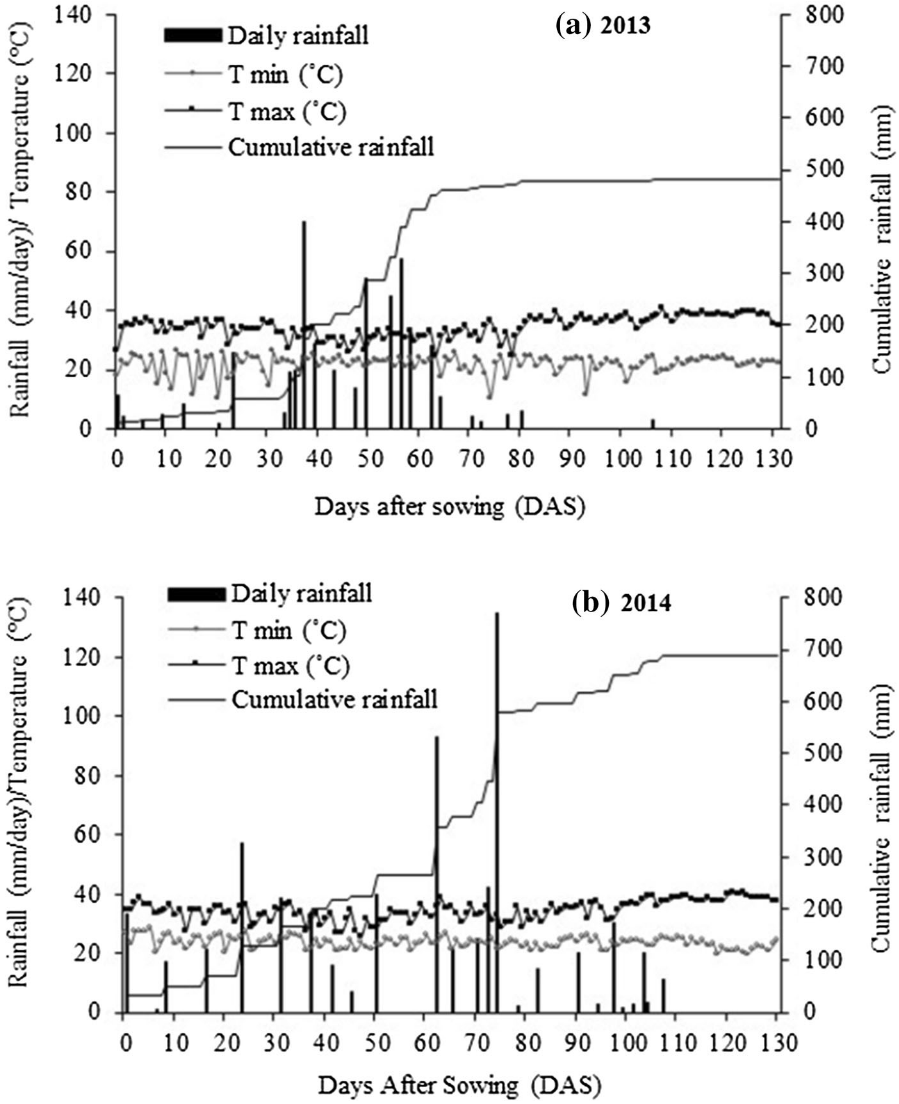



**Fig. 1** Rainfall distribution and temperatures in 2013 (upper panel) and in 2014 (lower panel)

planting, at planting and 15 days after planting respectively. To determine the millet grain yield and the dry matter yield (TDM), straw samples and manually threshed millet panicles, were harvested from the central 6 m × 6 m of each plot and sun-dried. Thereafter, the dried samples were weighed and expressed in kg $ha^{-1}$.

Millet nutrient utilization efficiency (NUE) was calculated with the equation used by Good et al. (2004) as follows:

$$\mathrm{NUE}(\mathrm{kg\,kg^{-1}}) = \frac{\mathrm{Yield}(\mathrm{kg\,ha^{-1}})}{\mathrm{Total\ nitrient\ absorbed}(\mathrm{kg\,ha^{-1}})} \tag{1}$$

where Yield = millet grain yield; Total nutrient absorbed by millet.

The decomposition and nutrient release patterns of manure, were studied using the litterbag technique. The litterbags made of 1 mm mesh size iron net, were filled with 100 g on dry mass basis of cattle manure. Eight (8) litterbags were randomly placed in the individual plots with one litterbag per zaï hole. The litterbags were collected at millet developmental stages (tillering, stem elongation, anthesis and at dough). At each collection stage, two (2) litterbags were taken from each experimental plot for manure dry weight and nutrient losses. Manure remaining in

**Table 1** Initial soil chemical and physical properties of the experimental field (n = 16)

| Parameters | Soil depth (0–20 cm) |
|---|---|
| Soil texture | |
| Sand (g $kg^{-1}$) | 748 ± 0.00 |
| Clay (g $kg^{-1}$) | 252 ± 0.00 |
| Soil chemical properties | |
| pH-$H_2O$ (1:2.5) | 4.5 ± 0.07 |
| pH-KCl (1:2.5) | 4.0 ± 0.07 |
| Total-N (mg $kg^{-1}$) | 272 ± 15.3 |
| P-Bray1 (mg $kg^{-1}$) | 6.4 ± 0.6 |
| OC (g $kg^{-1}$) | 3.4 ± 0.02 |
| Exchange acidity ($cmol_c$ $kg^{-1}$) | 0.54 ± 0.08 |
| Exchange base ($cmol_c$ $kg^{-1}$) | 0.91 ± 0.10 |
| Base saturation (%) | 62.5 ± 5.4 |
| Al saturation (%) | 27.3 ± 4.1 |

± Standard error

the litterbags at each collection time, was separated from soil and organic debris manually, and oven dried at 65 °C for 48 h to constant mass. The oven-dried samples were separately weighed to determine manure dry mass losses. Manure mass, was corrected for sand content after ignition at 550 °C using the method proposed by Kurzatkowski et al. (2004). Manure dry mass loss was calculated as a percentage of manure remaining relative to the amount initially applied.

To study manure decomposition trend, the exponential decay constant ($k$), was determined for dry mass and nutrients using a single exponential model described by Wider and Lang (1982) as follows:

$$Y_t = Y_0 e^{-kt} \quad (2)$$

where $Y_t$ = percent mass of manure remaining at time t, $Y_0$ = percent mass of manure initially; t = time (days); $k$ = exponential decay constant.

To calculate nutrients released at a specific litterbag collection time, the oven-dried remaining manure was ground and passed through 2 mm mesh sieve for N and P analysis. Nutrient release was calculated as the difference between the initial nutrient content in the amendment and the quantity remaining at sampling time (Fatondji et al. 2009).

To evaluate millet nutrient uptake with regard to nutrient released from manure, two plants from two zaï where litterbags were placed were sampled at the same period of litterbags collection i.e. at tillering, stem elongation, anthesis and dough stages.

## Soil and plant laboratory analysis

Soil samples were taken at the onset on the experiment before the rainy season from 0 to 20 cm in each plot. Each sample was analyzed for pH ($H_2O$) using pH meter (with a 1:2.5 soil:water ratio), organic carbon 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). Exchangeable bases ($Na^+$, $K^+$, $Ca^{2+}$ and $Mg^{2+}$) were determined by the ammonium acetate (NH4OAc) solution at pH 7 using the extraction method described by van Reeuwijk (1993). The exchangeable acidity ($H^+$ and $Al^{3+}$ was determined using the method described by van Reeuwijk (1993). The particle size distribution was determined using Robinson method as described by ICRISAT Soil and Plant Laboratory (Houba et al. 1995).

Plant samples collected at each litterbag picking stage, were separated into leaves, stems, glumes and grains where available, which were sun-dried thereafter. The dried samples were milled and subjected to total N and P analysis. Total nitrogen was analysed by Kjeldahl methods using a mixture of salicylic acid, sulphuric acid ($H_2SO_4$) and selenium for the digestion. The quantitative determination of total N, was done with an auto-analyzer using the colorimetric method based on the Bertholet reaction (Houba et al. 1995). The same digest was used to determine total P. The total P was quantified with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid.

It should be noted that prior to the experiment, manure applied each year was analyzed for N, P, K and organic carbon contents. Total N, P and organic carbon were analyzed using the methods described above. Total K was determined with flame emission spectrophotometry (Houba et al. 1995).

## Statistical analysis

Prior to analysis of variance (Anova), data were checked for variance normality using boxplots. Grain yield, total dry matter yield and nutrient utilization efficiency data were analysed using a General

Treatment Structure (in Randomized Blocks) in GenStat v. 9 (Lawes Agricultural Trust 2007). Percentage mass remaining was regressed on time using nonlinear regression models in GenStat v. 9. Data collected on the dry mass and nutrient remaining in decomposing manure were subjected to Anova using the AREPMEASURES procedure in GenStat. The differences among treatments were considered at a probability level $\leq 0.05$. Means were separated using least significant difference (LSD) at 5% confidence level.

## Results and discussion

### Initial characteristics of cattle manure applied

The initial characteristics of cattle manure applied in the current study are presented in Table 2. In both experimental years, the nitrogen (N) concentration in the manure was generally similar (about 15 g $kg^{-1}$). Nitrogen concentration was markedly higher than 2.9–3.5 g $kg^{-1}$ reported by Gonda et al. (2016) in Niger. However, Fatondji et al. (2009) reported N concentrations of manure relatively higher (17.4 and 25.3 g $kg^{-1}$) than those obtained in the present study. With regard to the threshold of 25 g N $kg^{-1}$ (Palm et al. 2001) as the determinant of N mineralization, manure applied in this study, is of low quality in terms of N content. However, due to scarcity of this material, access to better quality manure could not be achieved.

The potassium (K) concentrations were similar in the cattle manure applied in 2013 and 2014. Phosphorus (P) concentrations were 4.1 and 2.6 g $kg^{-1}$ in 2013 and 2014, respectively. These values were higher than the range of P concentrations (1.5–2.1 g $kg^{-1}$) in cattle manure reported from several studies conducted in Niger and compiled by Harris (2002). However, Esse et al. (2001) reported a P concentration in cattle manure lower (2 g $kg^{-1}$) than that obtained in the current study.

The large variation in nutrient concentration among manures applied in the various studies could be explained by the variation in animal diet regimes and also manure storage process in the different context.

The ash content was higher (80%) in 2014 than in 2013 (70%). This high value indicates high content of sand and inorganic minerals in the manure which is generally a common problem with manure from smallholder farms where manure usually accumulates on loose sandy soils. Even though, manure applied in the present study has not been collected from farmers' home yard, the storage conditions are similar. The C:N ratios (27.5 and 31.3) of the manure applied were greater than C:N ratio of 20–25 above which N would be potentially unavailable to crop due to net immobilization (Sileshi et al. 2016). The C:P ratios were 98.7 and 171.8 in 2013 and 2014, respectively. These values were within the range of < 200 set by Stevenson and Cole (1999) as the critical value for net P mineralization. Therefore, no or little P immobilization is expected from the manure applied in the present study. The N:P ratios were 3.8 in 2013 and 5.7 in 2014. These ratios appear to be lower with regard to the thresholds of < 15 set to be an indicator of N limitation during litter decomposition (Güsewell and Gessner 2009).

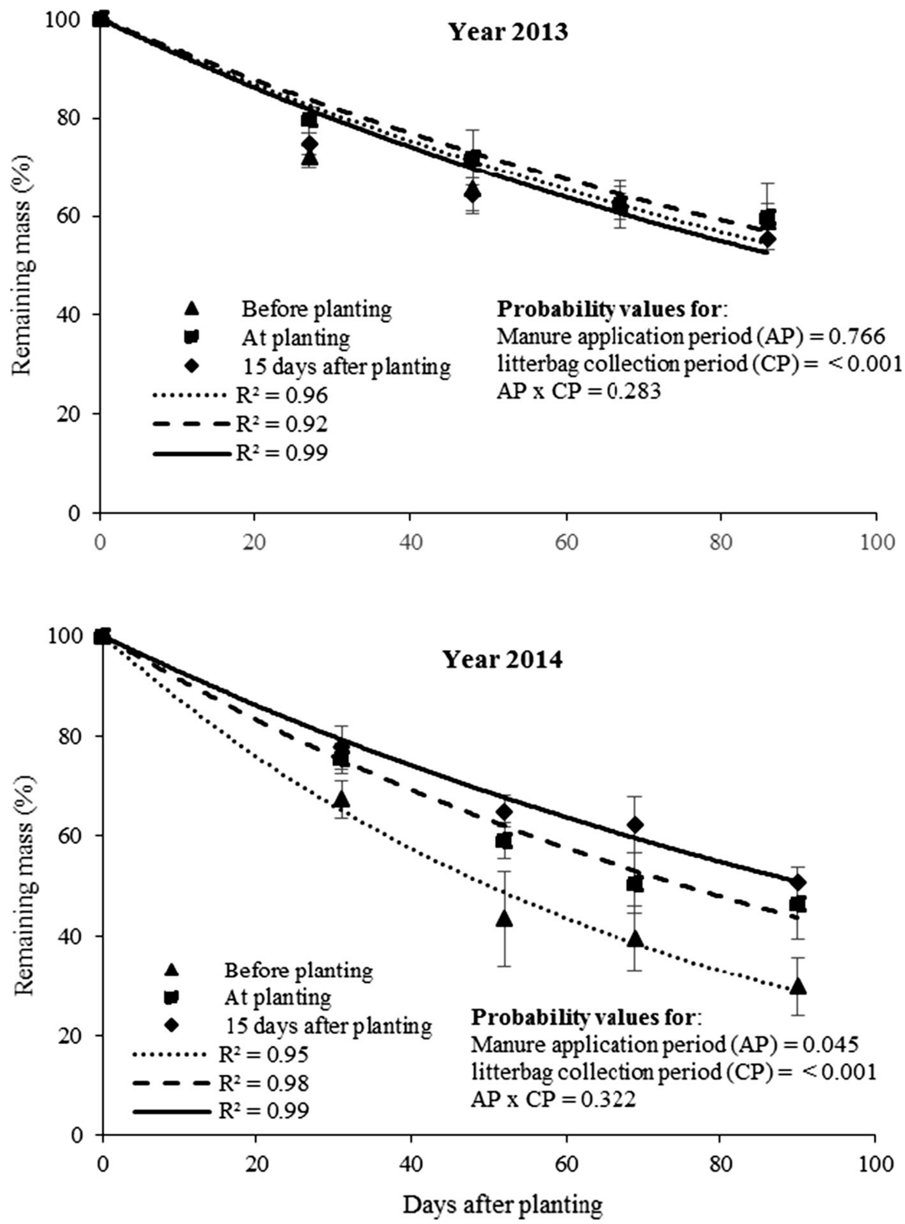
**Table 2** Chemical characteristics of farmyard manure tested (n = 3)

| Parameters | 2013 | 2014 |
|---|---|---|
| N (g $kg^{-1}$) | 14.7 | 14.9 |
| P (g $kg^{-1}$) | 4.1 | 2.6 |
| K (g $kg^{-1}$) | 13.0 | 11.0 |
| C (g $kg^{-1}$) | 404 | 447 |
| C:N ratio | 27.5 | 31.3 |
| C:P ratio | 98.5 | 171.8 |
| N:P ratio | 3.8 | 5.7 |
| Ash (g $kg^{-1}$) | 697 | 803 |

### Manure decomposition as affected by timing application

The Anova revealed no significant effects or interactions for both manure rate, and mineral fertilizer on the decomposition data and nutrient release. There was, no significant difference in manure mass losses in 2013 between manure application periods (Fig. 2a). However, in 2014 manure mass loss differed significantly ($p = 0.045$) with manure application periods (Fig. 2b). The highest dry mass loss occurred when manure was applied before planting with 70% of manure initially applied being decomposed at millet maturity stage followed by manure applied at planting with almost 50% of initial manure dry mass losses. It

**Fig. 2** Effect of application timing period on manure decomposition. Error bars indicate standard error of means




may be possible, that, a longer duration of manure in the field would result in a greater decomposition rate since the process of organic material decomposition triggers off as soon as the material is placed in the soil due to the presence of decomposers particularly termites which contribute much in organic materials decomposition in the Sahel (Mando and Brussaard 1999). However, the contribution of termite activities on manure decomposition was not recorded in the current study.

There was, a significant interaction ($p = 0.048$) between manure application periods and experimental year in manure exponential decay constant ($k$) values (Table 3). The $k$ values were markedly higher in 2014 with the highest $k$ value being recorded for manure applied before planting. The decay constant values ($k = 0.0101$–$0.0108$ day$^{-1}$) obtained in 2014 were lower than those ($k = 0.011$–$0.021$ day$^{-1}$) reported from manure decomposed in the zaï pits by Fatondji et al. (2009). The discrepancy in $k$ values between the

**Table 3** Effect of manure application period on decomposition coefficient-decay constant (k) $days^{-1}$

| Manure application period | 2013 | 2014 |
|---|---|---|
| Before planting | $0.0020^{c} \pm 0.0006$ | $0.0108^{a} \pm 0.0007$ |
| At planting | $0.0048^{b} \pm 0.0012$ | $0.0107^{a} \pm 0.0006$ |
| 15 days after planting | $0.0073^{a} \pm 0.0005$ | $0.0101^{a} \pm 0.0003$ |
| Probability values | | |
| Year (Y) | < 0.001 | |
| Application period (T) | 0.018 | |
| Y × T | 0.004 | |
| Lsd (5%) | | |
| Year (Y) | 0.0012 | |
| Application period (T) | 0.0015 | |
| Y × T | 0.002 | |

Mean in a column within an experimental year with similar letter are not significantly different at the 5% level according to the LSD test; ± standard error

two studies could be related to the difference in manure quality which was relatively better in the latter study. However, the presence of termites have significantly contributed to manure decomposition in the study mentioned earlier. The same study reported *k* value of 0.006 $day^{-1}$ when pesticide was used for termites' control.

The proportions of manure dry mass remaining at the millet maturity stage were on average 58% in 2013 and 41% in 2014 (Fig. 2). The difference in manure decomposition between the two cropping seasons could be attributed to the low soil moisture content in 2013 as a result of rainfall shortage during this cropping season (Fig. 1). In fact, the process of organic amendment decomposition involves soil microorganisms, that, require adequate soil moisture for maximum activity, the lack of sufficient soil moisture affects therefore decomposers activity and thereby decreasing the rate of organic amendment decomposition (Brockett et al. 2012; Vigil and Spark 2004).

## Nutrients released from decomposing manure versus nutrient absorbed by millet

The quantity of N released and N absorbed by millet is illustrated in Fig. 3. At early stage of millet development (55 days after sowing), the quantity of N absorbed by millet was low when compared to N released from decomposing manure (on average 4.9 versus 2.6 kg $ha^{-1}$ in 2013 and 11.2 versus 4.3 kg $ha^{-1}$ in 2014). However, there were no significant differences in N released from manure and also N absorbed by millet among the different manure application periods (Table 4). Millet N absorption represented on average 61, 52 and 33% of N released from decomposing manure when manure was applied before planting, at planting and 15 days after planting, respectively. The present results, indicate that, at early stage (55 days after sowing) of its development, millet is not able to absorb all the quantity of N released from manure. This asynchrony (lack of synchrony) between N released and N absorbed could increase the risk of N losses by leaching at early stage of millet development. However, the relatively higher proportion of absorbed to released N recorded when manure was applied before planting is an indication of reduced N losses compared to later application. In both years, the quantity of N absorbed from 55 days after planting (tillering stage) to maturity stage exceeded markedly the quantity of N released from manure irrespective of manure application periods. The present findings are consistent with those of Fatondji et al. (2009) who found the quantity of nutrient absorbed by millet was particularly higher than the quantity of nutrient released from decomposing manure after 39 days of millet growth. At maturity stage, the total quantity of N released from decomposing manure accounted on average for 36, 31 and 21% of N absorbed by millet when manure was applied before planting, at planting and 15 days after planting, respectively. It appears that apart from N released from manure, millet has used N from soil reserve and N applied from mineral fertilizer to satisfy its needs.

The proportions of P absorbed by millet at tillering was relatively lower compared to those of N. There

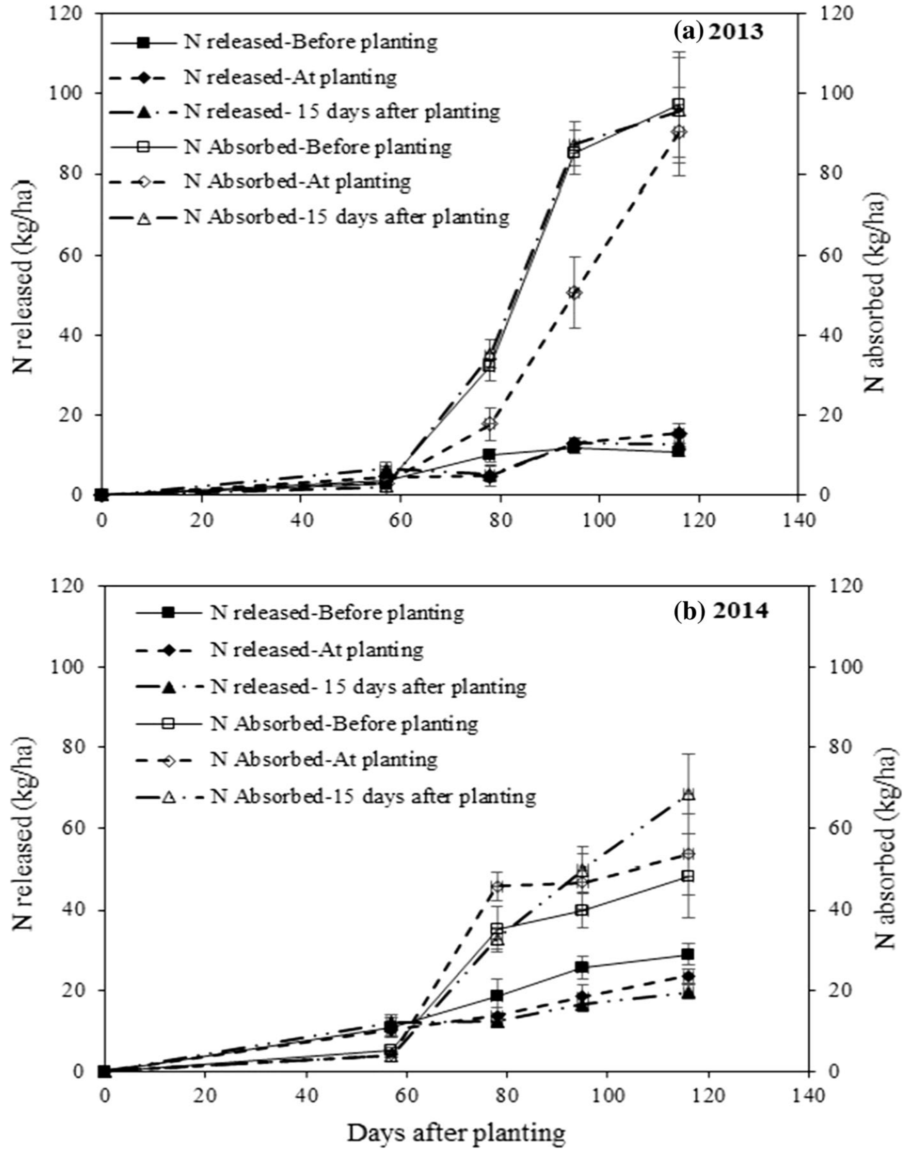



**Fig. 3** N released from decomposing manure and N absorbed by millet. Vertical lines indicate standard error of means

**Table 4** Probability values (0.05) of manure application period effect on N and P released and absorbed

| | 2013 | | 2014 | | 2013 | | 2014 | |
|---|---|---|---|---|---|---|---|---|
| | N released | N absorbed | N released | N absorbed | P released | P absorbed | P released | P absorbed |
| Tillering | 0.142 | 0.304 | 0.245 | 0.464 | 0.049 | 0.665 | 0.660 | 0.182 |
| Elongation | 0.014 | 0.009 | 0.026 | 0.045 | 0.024 | 0.014 | 0.109 | < 0.001 |
| Flowering | 0.750 | 0.023 | 0.048 | 0.007 | 0.442 | 0.771 | 0.008 | < 0.001 |
| Maturity | 0.840 | 0.240 | 0.027 | 0.042 | 0.015 | < 0.001 | 0.029 | 0.059 |

was, a significant difference ($p = 0.046$) in P released among manure application periods (Table 5) at tillering in 2013 with P released relatively higher being similarly recorded when manure was applied before planting and at planting (Fig. 4a). However, no significant differences in P released and P absorbed

**Table 5** Millet grain yield and total dry matter

| Manure application period | Mineral fertilizer | Grain yield (kg ha$^{-1}$) | | Total dry matter (kg ha$^{-1}$) | |
|---|---|---|---|---|---|
| | | 2013 | 2014 | 2013 | 2014 |
| Before planting | 0 g NPK per hill | 560 ± 57 | 1048 ± 123 | 4610 ± 264 | 3790 ± 249 |
| | 6 g NPK per hill | 670 ± 19 | 1026 ± 109 | 4178 ± 431 | 4212 ± 323 |
| At planting | 0 g NPK per hill | 654 ± 78 | 659 ± 32 | 3256 ± 376 | 3510 ± 177 |
| | 6 g NPK per hill | 387 ± 15 | 1146 ± 37 | 4211 ± 325 | 3790 ± 220 |
| 15 days after planting | 0 g NPK per hill | 665 ± 33 | 412 ± 37 | 2756 ± 463 | 3298 ± 146 |
| | 6 g NPK per hill | 775 ± 75 | 908 ± 119 | 3679 ± 185 | 4499 ± 206 |
| Probability (5%) | | | | | |
| Year (Y) | | < 0.001 | | 0726 | |
| Manure application period (T) | | 0.013 | | 0.030 | |
| Mineral fertilizer (F) | | < 0.001 | | 0.008 | |
| Y × T | | < 0.001 | | 0.085 | |
| Y × F | | < 0.001 | | 0.695 | |
| T × F | | 0.022 | | 0.097 | |
| Y × T × F | | < 0.001 | | 0.280 | |
| CV (%) | | 24.7 | | 25.1 | |

± Standard error

have been detected among manure application periods in 2014 at tillering (Table 4). In general, the quantity of P removed by millet at tillering represented on an average 15, 12 and 15% of P released from manure applied before planting, respectively. At this stage, millet crop has not grown enough to make use of all the quantity of P released (Fig. 4). The advantage of early release of P from the decomposing manure is that, it enhances root growth during early crop stages. Overall, the amounts of P absorbed by millet at tillering (on average 0.35 kg ha$^{-1}$ in 2013 and 0.82 kg ha$^{-1}$ in 2014) were negligible compared to those released by manure (similarly 4.2 kg ha$^{-1}$ in 2013 and 2014). It is likely that rapid release of P at early stage (tillering) of millet development explains the low P absorption recorded since at this stage the demand of crop in P seems to be low. However, the shortfall in P absorption by millet at this stage is not necessarily negative in terms of P losses. Leaching of phosphorus in the soils is generally low (Djodjic et al. 2004). This positive aspect of phosphate staying where it is released is important because the nutrient can be eventually used during advanced crop growth stage. At millet maturity, P released from decomposing manure was significantly different ($p < 0.05$) among manure application periods in both years (Table 4). Significant differences ($p < 0.001$) were also detected in P absorbed by millet particularly in 2013 with the highest P absorption being recorded when manure was applied 15 days after planting followed by manure applied at planting. The amounts of P absorbed by millet at this stage were generally 2 times higher than the amounts of P released from decomposing manure irrespective of manure application periods. It is possible, that, in addition to P released at initial stage of millet development which was not entirely absorbed, millet has made use of other sources of P possibly P applied from native soil and mineral fertilizer applied to satisfy its P requirement for the level of yield produced.

## Grain yields and total dry matter yields

Manure application period significantly ($p = 0.013$) influenced millet grain yield irrespective of mineral fertilizer application (Table 5). Early application of manure (before planting) increased millet grain yield on average by 16 and 20% compared to manure applied at planting and 15 days after planting, respectively.

Similarly, the total dry matter (TDM) yields varied significantly ($p = 0.030$) according to the manure application period. Application of manure prior to planting led to an increase in TDM yields by 14 and

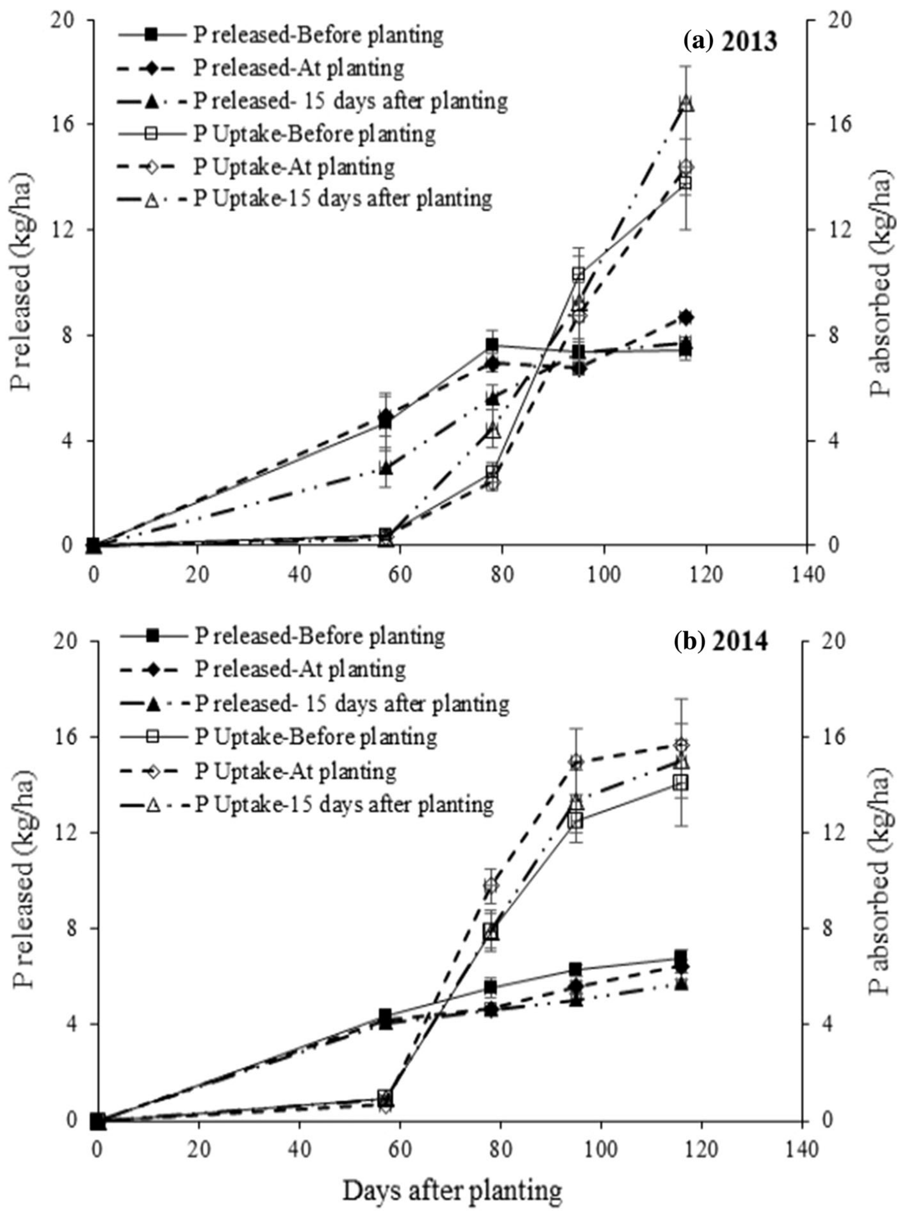



**Fig. 4** P released from manure and P absorbed by millet. Error bars indicate standard error of means

18% compared to the application of manure at planting and 15 days after planting, respectively.

The present findings seem to be consistent with other research which found an increase in crop yield with the application of poultry manure prior to planting (Kolawole 2014; Mkhabela and Materechera 2013). Early application of organic amendment may lead an increase in manure comminution by termites which facilitates its decomposition by microorganisms and thereby enhances release of nutrients readily available at the early stage of crop development. The significant yields increase due to early application of manure can be related to the early P mineralization from decomposing manure which may stimulate rapid millet root growth and improved nutrient uptake. Akponikpé et al. (2008) reported that delayed application of organic amendment reduces its positive impact on millet growth and yields due to a reduction in nutrients mobilization.

Application of mineral fertilizer significantly ($p < 0.001$) increased millet grain yields and total dry matter production (Table 5). The highest millet grain and total dry matter yields were found when 6 g of NPK fertilizer was added in the zaï pit. The application of 6 g of NPK fertilizer per zaï pit, increased millet grain yield on average by 23% and total dry matter yield by 16% compared to control (without mineral fertilizer application). Increase in millet grain yield associated with mineral fertilizer application could be explained by the low inherent fertility of degraded soil used in the current study, which leads to positive responses following any improved soil fertility management practice (Ibrahim et al. 2015a). Addition of mineral fertilizer combined with different periods of manure application has induced a synergetic effect on millet grain yield ($p = 0.002$). Millet grain yields increased on average by 5, 17 and 57% when 6 g of NPK per zaï pit were added in the plots that received manure application before planting, at planting and 15 days after planting, respectively. These results, indicate that farmers who cannot afford to apply mineral fertilizer at planting could delay the application of manure for increased crop yields. However, the effects of manure application period and mineral fertilizer on millet total dry matter production in the current study were additive.

There was a significant ($p < 0.001$) year-effect on millet grain yields recorded in the current study. The highest grain yields were obtained in 2014 compared to 2013 (Table 5). Several experiments conducted in the Sahel have found year-effect on millet yields (Akponikpé et al. 2008; Gonda et al. 2016; Ibrahim et al. 2015b). The seasonal yield variability in millet grain yield could be attributed to the larger amount and better rainfall distribution observed throughout the growing period in 2014 (Fig. 1) which ultimately favoured better plant growth and thereby increasing millet yield. Dry spell periods as observed in 2013, are known to hamper plant nutrients uptake and translocation especially when they occur during flowering and grain filling and subsequently reduces crop productivity. Another possible explanation, for yields variability observed in the current study might be that, the residual fertilizing effect of manure applied in the previous year (2013) has enhanced nutrients supply in 2014 since at crop harvest in 2013, only 42% of manure applied have been decomposed. Kirchmann (1985) showed that the first crop grown on soil after amendment with manure generally utilises 15–35% of the manure N and the others amounts are recovered in subsequent crops.

Millet nutrient utilization efficiency as affected by manure application periods

Millet N utilization efficiency was significantly ($p = 0.004$) higher when manure was applied before planting compared to the application of manure at planting or 15 days after planting (Table 6). Application of manure prior to planting (before planting), increased N utilization efficiency on an average by 25 and 31% compared to the application of manure at planting and 15 days after planting respectively. Likewise, P applied was more efficiently ($p = 0.032$) utilized (PUE) with early application of manure compared to the application of manure at planting or 15 days after planting. Application of manure before planting, has led to an increase in PUE of 20 and 22% compared to manure applied at planting and 15 days after planting, respectively. These results, suggest that in the context of the present study even though nutrient release from manure applied prior to planting was faster than the rate of nutrient uptake, millet nutrient demand was met in the course of crop growth, which has led to the high nutrient use efficiency recorded with this application period. The results of the current study are consistent with those of Cassman et al. (2002), who reported that plant growth and nutrient use efficiency are improved when crop nutrients demand meets supply.

Nitrogen utilization efficiency varied significantly ($p < 0.001$) with cropping season. The quantity of N absorbed by millet in 2014 was utilized more efficiently regardless of manure application period compared to that of 2013. Possible explanation of the relatively low efficient utilization of N recorded in 2013 was probably, the scarcity of rainfall due to the occurrence of dry spells during the crop growing period, which reduced millet growth and thereby decreased crop yields.

## Conclusion and recommendations

The results from this study indicated that under adequate moisture conditions, the earlier the manure was placed in the zaï pits, the faster decomposition proceeded with consequent nutrient release. However, plant growth does not follow this rapid trend of nutrient release exposing nutrients to risk of losses through leaching particularly N. It was observed in the present study that application of manure prior to

**Table 6** N and P utilization efficient as affected by manure application period

| Manure application period | NUE (kg $kg^{-1}$) | | PUE (kg $kg^{-1}$) | |
|---|---|---|---|---|
| | 2013 | 2014 | 2013 | 2014 |
| Before planting | $75^a \pm 7$ | $114^a \pm 41$ | $425^a \pm 7$ | $294^a \pm 9$ |
| At planting | $68^a \pm 6$ | $84^b \pm 20$ | $344^b \pm 9$ | $254^a \pm 20$ |
| 15 days after planting | $52^b \pm 4$ | $93^b \pm 25$ | $321^b \pm 6$ | $269^a \pm 22$ |
| Probability (5%) | | | | |
| Year (Y) | < 0.001 | | < 0.001 | |
| Manure application period (T) | 0.004 | | 0.032 | |
| Y × T | 0.106 | | 0.321 | |
| CV (%) | 19.7 | | 19.9 | |

Mean in a column within an experimental year with similar letter are not significantly different at the 5% level according to the LSD test; ± standard error

planting led to higher quantity of nutrients released from decomposing manure under zaï pit, increased millet yields and enhanced millet nutrient utilization efficiency by meeting plant nutrients demand in the course of crop growth. However to minimize further the risk of nutrient losses from manure applied before planting, the option of split application can be explored to provide the start-up nutrients to the crop at planting and apply the rest at planting or early after planting. The aspect of split application of manure is the subject of the second part of this study where we explored the mode of application that would enhance better synchronicity between nutrient release and crop need particularly at initial stage of crop development.

In general, considering that not all manure was decomposed in the course of the season, it seems that the application of 2000 kg $ha^{-1}$ of manure is not sufficient enough to provide the quantity of nutrient required for optimal millet production under degraded soil as crop nutrient absoption was beyond the quantity provided by the decomposed manure. Therefore, we recommend to supplement manure with mineral fertilizer to improve and sustain the fertility of this degraded soil and millet production.

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## References

Akponikpé PBI, Michels K, Bielders CL (2008) Integrated nutrient management of pearl millet in the Sahel combining cattle manure, crop residues and mineral fertilizer. Exp Agric 44:453–472

Boubacar MM, Abdoulaye D, Salamatou IA, Jørgen AA, Ambouta KJM, Mahamane A (2016) Combined traditional water harvesting (Zaï) and mulching techniques increase available soil phosphorus content and millet yield. J Agric Sci 8(4):126

Bouzou MI, Dan Lamso N (2004) Le «tassa»: une technique de conservation des eaux et des sols bien adaptée aux conditions physiques et socio-économiques des glacis des régions semi-arides (Niger). Rev Geogr Alp 92:61–70

Brockett BF, Prescott CE, Grayston SJ (2012) Soil moisture is the major factor influencing microbial community structure and enzyme activities across seven biogeoclimatic zones in western Canada. Soil Biol Biochem 44:9–20

Cassman KG, Dobermann A, Walters DT (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management. AMBIO J Hum Environ 31:132–140

Djodjic F, Börling K, Bergström L (2004) Phosphorus leaching in relation to soil type and soil phosphorus content. J Environ Qual 33:678–684

Esse P, Buerkert A, Hiernaux P, Assa A (2001) Decomposition of and nutrient release from ruminant manure on acid sandy soils in the Sahelian zone of Niger, West Africa. Agric Ecosyst Environ 83:55–63

Fatondji D, Martius C, Bielders C, Vlek PLG, Bationo A, Gerard B (2006) Effect of planting technique and amendment type on pearl millet yield, nutrient uptake, and water use on degraded land in Niger. Nutr Cycl Agroecosyst 76:203–217

Fatondji D, Martius C, Zougmore R, Vlek PL, Bielders C, Koala S (2009) Decomposition of organic amendment and nutrient release under the zai technique in the Sahel. Nutr Cycl Agroecosyst 85:225–239

Gandah M, Brouwer J, Hiernaux P, Duivenbooden NV (2003) Fertility management and landscape position: farmers' use of nutrient sources in western Niger and possible improvements. Nutr Cycl Agroecosyst 67(55):66

Gascho GJ, Menezes RS, Hanna WW, Hubbard RK, Wilson JP (1995) Nutrient requirement of Pearl Millet. In: First national grain Pearl Millet symposium, Conference Proceedings. University of Georgia, Cooperative Extension Service, Tifton, pp 92–97

Gonda A, Ewusi Mensah N, Maman N, Francis Marthy T, Ebnezer Yeboah S, Robert Clement A (2016) Nutrient release patterns of compost and its implication on crop yield under Sahelian conditions of Niger. Nutr Cycl Agroecosyst 105:1–14

Good AG, Shrawat AK, Muench DG (2004) Can less yield more? Is reducing nutrient input into the environment compatible with maintaining crop production? Trends Plant Sci 9:598–605

Güsewell S, Gessner MO (2009) N:P ratios influence litter decomposition and colonization by fungi and bacteria in microcosms. Funct Ecol 23:211–219

Harris F (2002) Managment of manure in farming systems in Semi-Arid West Africa. Exp Agric 38:131–148

Houba V, Van der Lee J, Novozamsky I (1995) Soil analysis procedures; other procedures (soil and plant analysis, part 5B). Department of Soil Science and Plant Nutrition, Wageningen Agricultural University

Ibrahim A, Abaidoo RC, Fatondji D, Opoku A (2015a) Determinants of fertilizer micro-dosing-induced yield increment of pearl millet on an acid sandy soil. Exp Agric 52:1–17

Ibrahim A, Abaidoo RC, Fatondji D, Opoku A (2015b) Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system. Field Crops Res 180:29–36

Kaboré D, Reij C (2004) The emergence and spreading of an improved traditional soil and water conservation practice in Burkina Faso. Environment and Production Technology Division discussion paper 114. http://www.ifpri.org/event/conferences/2003/120103/papers/paper10.pdf

Kirchmann H (1985) Losses, plant uptake and utilisation of manure nitrogen during a production cycle [cattle manure, poultry manure, NH3 volatilisation, denitrification, non-symbiotic N2 fixation] Sveriges Lantbruksuniv

Kolawole GO (2014) Effect of time of poultry manure application on the performance of maize in Ogbomoso, Oyo State, Nigeria. J Appl Agric Res 6:253–258

Kurzatkowski D, Martius C, Hoefer H, Garcia M, Forster B, Beck L, Vlek P (2004) Litter decomposition, microbial biomass and activity of soil organisms in three agroforestry sites in central Amazonia. Nutr Cycl Agroecosyst 69:257–267

Lahmar R, Bationo BA, Dan Lamso N, Guéro Y, Tittonell P (2012) Tailoring conservation agriculture technologies to West Africa semi-arid zones: building on traditional local practices for soil restoration. Field Crops Res 132:158–167

Lawes Agricultural Trust (2007) Genstat. Lawes Agricultural Trust (Rothamsted ExperimentalStation), Rothamsted

Mafongoya PL, Giller KE, Palm CA (1998) Decomposition and nitrogen release patterns of tree prunings and litter. Agrof Syst 38:77–97

Mando A, Brussaard L (1999) Contribution of termites to the breakdown of straw under Sahelian conditions. Biol Fertil Soils 29:332–334

Mkhabela TS, Materechera SA (2013) Influence of kraal manure application time on emergence, growth and grain yield of maize grown in two soils with contrasting textures. J Food Agric Environ 11:422–427

Ouattara B, Hien V, Lompo F (1999) Development of water management technologies for rainfed crops in Burkina Faso. In: van Duivenbooden N et al. (eds). Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia and North and Sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) Workshops of the optimizing soil water use (OSWU) Consortium, Aleppo, Syria, ICARDA, and Patancheru, India, ICRISAT, pp 265–281

Palm CA, Gachengo CN, Delve RJ, Cadisch G, Giller KE (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosys Environ 83:27–42

Pasternak D, Senbeto D, Nikiema A, Kumar S, Fatondji D, Woltering L, Ratnadass A, Ndjeunga J (2009) Bioreclamation of degraded African lands with women empowerment. Chronica Hortic 49:24–27

Roose E, Kabore V, Guenat C (1993) Le zaï: fonctionnement, limites et amélioration d'une pratique traditionnelle africaine de réhabilitation de la végétation et de la productivité des terres dégradées en région soudano-sahélienne (Burkina Faso). Cahiers-ORSTOM. Pédologie 28:159–173

Roose E, Kaboré V, Guenat C (1999) Zai practice: a West African traditional rehabilitation system for semiarid degraded lands, a case study in Burkina Faso. Arid Soil Res Rehabil 13:343–355

Schlecht E, Buerkert A, Tielkes E, Bationo A (2006) A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. Nutr Cycl Agroecosyst 76:109–136

Sileshi GW, Nhamo N, Mafongoya PL, Tanimu J (2016) Stoichiometry of animal manure and implications for nutrient cycling and agriculture in sub-Saharan Africa. Nutr Cycl Agroecosyst 106:1–15

Stevenson FJ, Cole MA (1999) Cycles of soils: carbon, nitrogen, phosphorus, sulphur, micronutrients. Wiley, New York

Tabo R, Bationo A, Amadou B, Marchal D, Lompo F, Gandah M, Hassane O, Diallo MK, Ndjeunga J, Fatondji D, Gerard B, Sogodogo D, Taonda JBS, Sako K, Boubacar S, Abdou A, Koala S (2011) Fertilizer microdosing and "warrantage" or inventory credit system to improve food security and farmers' income in West Africa. In: Bationo A, Waswa B, Okeyo JM, Maina F, Kihara JM (eds) Innovations as key to the green revolution in Africa. Springer, Netherlands, pp 113–121

van Reeuwijk LP (1993) Procedures for soil analysis. Technical paper No 9, Fourth Edition edited by the International Soil Reference and Information Center (ISRIC)

Vigil MF, Spark D (2004) Factors affecting the rate of crop residue decomposition under field conditions. Conservation tillage Fact Sheet 33-95. USDA-ARS and USDA-NRCS, Akron, Colorado

Voortman RL (2010) Exploration into African land ecology on the chemistry between soils, plants and fertilizers, Ph.D. Dissertation, Wageningen Unversity

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38

Wider RK, Lang GE (1982) A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology 63:1636–1642

Wildemeersch JCJ, Garba M, Sabiou M, Steven S, Cornelis W (2015) The effect of water and soil conservation (WSC) on

the soil chemical, biological and physical quality of a plinthosol in Niger. Land Degrad Dev 73:773–783
Zingore S, James M, Beverly A, Lulseged T, Kihara J (2015) Soil degradation in sub-Saharan Africa and crop production options for soil rehabilitation. Better Crops Plant Food 99:24–26
Zougmoré R, Zida Z, Kambou N (2003) Role of nutrient amendments in the success of half-moon soil and water conservation practice in semiarid Burkina Faso. Soil Tillage Res 71:143–149