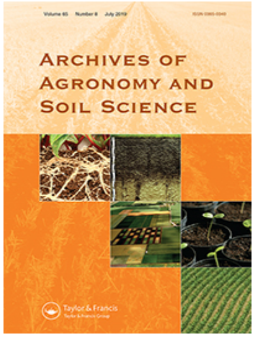

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Combined use of millet glume-derived compost and mineral fertilizer enhances soil microbial biomass and pearl millet yields in a low-input millet cropping system in Niger

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ABSTRACT

A two-year field experiment was conducted in Niger to explore the effects of integrated use of millet glume-derived compost (MGD-Compost) and NP fertilizer on soil microbial biomass carbon (C_{mic}), nitrogen (N_{mic}) and millet yields. Three compost rates (3000 kg ha^{-1}, 1500 kg ha^{-1} and 0 kg ha^{-1}) and three NP fertilizer rates (100%, 50% and 0% of recommended NP fertilizer) were arranged in a factorial experiment organized in a randomized complete block design with three replications. Combined application of compost and NP fertilizer induced a synergistic effect on C_{mic} and N_{mic}. Compost application increased millet grain yield from 59% to 91% compared to control. Combined application of compost and NP fertilizer increased millet grain yields from 57% to 70% in 2013 and from 36% to 82% in 2014 compared to sole application of mineral fertilizer. Agronomic efficiency (AE) of nitrogen values increased by 3.7 and 2.3 times than those of sole NP fertilizer application in 2013 and 2014, respectively. Phosphorus AE was 1.6 times higher than that of the sole application of NP fertilizer. These findings indicate that integrated application of MGD-Compost and NP fertilizer enhances soil microbial biomass content and increases millet grain yield in a low-input cropping system.

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KEYWORDS
Low-input; productivity; composting; millet; nutrient use efficiency (NUE)

Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.], is a main food cereal crop grown mostly in marginal environments in the arid and semi-arid tropical regions of Africa (Vadez et al. 2012). Peal millet grains form a basic component in the diet of a large human population in these regions while the stovers are used for animals feeding, mulching, construction materials and also as source of fuel (Bidinger and Hash 2004). Pearl millet is a central component of the food security of the rural poor in dry areas particularly in Niger where it is widely cultivated (Manyame 2006; Vadez et al. 2012). However, millet yields are still low due to poor soil fertility and unpredictable rainfall patterns (Suzuki et al. 2017). Lack of appropriate soil nutrient replenishment interventions coupled with inherent low soil organic matter status remain the main reasons for the soil fertility decline in Niger (Bationo et al. 1998).

The use of mineral fertilizer has been advocated as plausible soil fertility intervention that would lead to increased crop yields (Kihara et al. 2007). However, accessibility of mineral fertilizer to small-

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scale farmers' remains difficult due to their limited income (Abdoulaye and Sanders 2005). Consequently, Buerkert et al. (2002) suggested that the combined application of mineral fertilizer and organic resources could be an appropriate strategy to ameliorate soil fertility and improve crop productivity. However, several studies have indicated that the use of organic resources for crop production in the Sahel is a great challenge due to the competitive uses and limited availability of these materials (Powell and Unger 1997; Bationo et al. 1998; Opoku 2011; Valbuena et al. 2014). In another development, Fatondji et al. (2009) reported that organic amendments including animal manure and crop residues applied by farmers are generally inadequate in terms of quality and quantity for substantially increased crop yields. There is, therefore a need, to develop appropriate soil fertility management practices which would improve the fertilizer value of available organic materials for enhancing soil productivity and thereby increase crop yields under low-input cropping systems.

Millet glume (residues left after threshing of millet) is a potential source of organic amendment in Niger, the second world largest producer of millet (Obilana 2003). Millet glume contains reasonable quantities of macro and micro-nutrients (Tarfo et al. 2001). However, the main challenge associated with direct use of this organic material is its low nutrient release due to its relatively high lignin content which limits nutrient availability for increased crop productivity. There is, therefore, a need to improve the fertilizer value of millet glume for enhanced nutrient release and target the application of this resource for increasing crop yield and ensuring food security for smallholder farmers in the Sahel.

Composting is a biological decomposition process of organic materials and considered as a good way for recycling organic materials in a stabilized end-product for agriculture use (Bernal et al. 2009). Generally, compost application to soils stimulates microbial biomass which acts as a source-sink in nutrient cycling and as a driving force in nutrient availability for improved crop yield production (Wang et al. 2007; Moreno et al. 2012). Compost application has been shown to increase soil structural stability, soil water holding capacity, reducing soil loss and decreasing soil bulk density and thereby increasing soil workability (Martínez-Blanco et al. 2013). Furthermore, other studies have reported that regular addition of compost enhanced both soil C and N stocks and resulted in N and C build-up (Nevens and Reheul 2003; Diacono and Montemurro 2011). The use of MGD-compost as soil amendment is limited in the Sahelian low-input cropping systems. Knowledge about the potential effect of MGD-compost in different combinations with other sources of nutrients such as phosphorus and nitrogen, the two most commonly limiting nutrients in the Sahel (Bationo et al. 1992; Fofana et al. 2008) on soil microbial growth would help provide better insight for recommending appropriate MGD-compost to improve soil fertility status and thereby enhance millet yields in the Sahel. The novelty of the present study is then in addressing this knowledge gap which has an important implication for diversifying the source of nutrients for soil fertility improvement in the biomass-scarce environment such as the Sahelian regions. The objective of this study was to explore the potential of integrated use of MGD-compost and mineral fertilizer for increased soil microbial biomass and millet yields. We hypothesized that combined application of MDG-compost and mineral fertilizer enhances soil microbial biomass and increases millet yield.

Materials and methods

Description of experimental site

The experiment was conducted during the 2013 and 2014 at the Centre Régional de Recherche Agronomique du Niger (INRAN), Research Station located in N'dounga (13°25′00″ N and 2°18′28″ E). The average annual rainfall over the last fourteen (14) years at the experimental site is 510 mm (Climate database, CERRA-Kollo). The soils are classified as Psammentic Paleustalf in the USDA Soil Taxonomy. These soils are moderately acidic and characterized by low organic matter and low water holding capacity due to their coarse textured feature (Table 1). The initial microbial biomass was almost null in the soil (data not shown) which is most like due to the fact that the soil sampling has

Table 1. Initial soil chemical, microbiological and physical properties of the experimental site.

Measured parameters	Soil depth (0–15 cm)
Soil chemical	
pH-H_2O (1:2.5)	5.83
Organic carbon (mg kg^{-1})	800
Total N (mg kg^{-1})	100
Available P (mg kg^{-1})	13.57
Exchangeable bases ($cmol_{(+)}$ kg^{-1})	0.93
Exchangeable acidity ($cmol_{(+)}$ kg^{-1})	0.03
Soil texture	
Sand (%)	96.04
Silt (%)	1.92
Clay (%)	3.02

been done in dry season and soil was not wet. Generally, soil microbial biomass and activities seem to be minimal as a result of restricted soil moisture content (Tian et al. 2007; Brockett et al. 2012).

Experimental set-up

The experiment was a 3 × 3 factorial experiment organized in a randomized complete block design with three replications. The treatments consisted of factorial combinations of three levels of mineral fertilizer (100%, 50% and 0% of the recommended dose of N and P fertilizer in the study area which is 30 kg N ha^{-1} and 13 kg P ha^{-1}) and three application rates of MGD-compost (3000 kg ha^{-1}, 1500 kg ha^{-1} and 0 kg ha^{-1}). MGD-compost was applied in the planting holes at sowing. The planting holes consisted of the small planting hills of 15 cm diameter and 15 cm depth dug in the experimental plots (Ibrahim et al. 2015). In each planting hole, 300 g $hill^{-1}$, 150 g $hill^{-1}$, or 0 g $hill^{-1}$ corresponding to 3000 kg ha^{-1}, 1500 kg ha^{-1} and 0 kg ha^{-1} were applied respectively for a planting density of 10,000 hill ha^{-1}. Phosphorus fertilizer in the form of single superphosphate was applied two weeks after sowing while N as urea fertilizer was split applied at two weeks after sowing and at 50% flowering stage.

Preparation and characterization of MGD-compost

Millet glume and goat manure were mixed in the ratio of 2:1 The pile was watered with 0.1 m^3 once every ten (10) days to soften the substrate and thus facilitate degradation by decomposers. The compost materials were then buried in a pit of 2 m × 2 m × 1 m dimensions and covered with polyethene sheet to minimize moisture losses. Fifteen days later, 20 kg of fresh manure and 1.5 kg of urea mixture was prepared and incubated for three days for the proliferation of decomposer populations involved in the composting process. The pile was watered with 100 L water once every ten days to soften the substrate and thus facilitate degradation by decomposers. Several holes were made in the polyethene sheet using a wooden rod to allow aeration/ventilation, hence oxygen was needed by microorganisms for their growth over the period. In addition, the pile was turned after every ten days with a shovel to ensure a homogenous mixture of the compost materials, water and air. Watering of the pile was eventually-stopped after sixty days of composting. At 85 days of composting, the matured MGD-compost was then air-dried in a greenhouse and then stored in bags prior to field application.

Representative samples of MGD-compost were taken and ground to pass through a 1 mm mesh sieve after which organic carbon, total nitrogen, phosphorus, potassium, magnesium and calcium in the samples were determined as described by Motsara and Roy (2008). Polyphenol and lignin contents of the samples were also determined following the method of Anderson and Ingram (1993).The chemical composition of MGD-compost is presented in Table 2. The N content was 14 g kg^{-1} and P and K contents were 3.1 g kg^{-1} and 0.3 g kg^{-1}, respectively. The C/N ratio of compost was 7.9. The contents of lignin and polyphenol were 59.5 g kg^{-1} and 16.5 g kg^{-1}, respectively.

Table 2. Chemical characteristics of MGD-compost (n = 3).

Parameters	MGD-Compost
Total N (g kg^{-1})	14.0 ± 0.1
Total P (g kg^{-1})	3.1 ± 0.2
Total K (g kg^{-1})	0.8 ± 0.3
Organic carbon (g kg^{-1})	111.6 ± 7.7
Polyphenol (g kg^{-1})	16.5 ± 2.9
Lignin (g kg^{-1})	59.5 ± 5.0
C:N ratio	7.9 ± 2.3

n, number of sample analysed; ± standard error.

Crop management and calculations

About 15 seeds of millet (Haini Kiré Précose, so-called HKP) were sown in the planting hole at the onset of the rainy seasons, on 2nd July in 2013 and 26th June in 2014. The individual plot size measured 4 m × 6 m each and separated by a 2 m alley. The planting density was 10,000 hills ha^{-1} (1 m × 1 m) as recommended by Institut National de la Recherche Agronomique du Niger. Seedlings were thinned to 2 plants $hill^{-1}$ two weeks after planting followed by weeding. Three weeding events were undertaken during each cropping season. Harvesting was done at millet maturity stage on 25th October in 2013 and 15th October in 2014. To measure millet grain and dry matter yield, samples of panicles and straw were harvested from the 3 central rows (3 m × 5 m) of each plot. The samples were sun-dried for three weeks and the panicles manually-threshed. The millet grain and straw were weighed and expressed in kg ha^{-1}. In order to appreciate how much productivity improvement was gained by use of the nutrients inputs and how productive the cropping system is relative to its nutrient input, agronomic efficiency was calculated from the formula developed by Vanlauwe et al. (2011) as follows:

$$\text{Agronomic efficiency AE} = (Y - Y_0)/F_n \tag{1}$$

where;

Y = grain yield of a fertilized plot, Y_0 = grain or biomass yield of the control plot, F_n = amount of nitrogen or phosphorus applied.

Rainwater use efficiency (RUE) used as a proxy for water use efficiency was calculated as follows:

$$\text{Rainwater use efficiency} = \frac{Y}{R} \tag{2}$$

where Y is grain yield (kg ha^{-1}) and R is the total seasonal rainfall recorded from sowing to harvest (mm)

Soil sampling and analysis

In order to assess the initial soil physical and chemical properties of the experimental field, one composite soil sample consisting of 12 cores was collected at a depth of 0–15 cm from each plot using an auger on May 2013 before amendment application and sowing. One part of soil samples was stored in a refrigerator at 5 □ for initial microbial biomass nitrogen and carbon determination while the other part was subjected to initial chemical and textural analyses after air-drying and sieving through a 2 mm mesh sieve. Immediately after harvest in both 2013 and 2014, one composite soil sample was collected underneath of 12 planting hills in each plot for soil chemical and microbial biomass C and N analysis. Each sample was analysed for pH (H_2O) using a pH meter (with a 1:2.5 soil: water ratio), organic carbon, by modified Walkley and Black (1934) which employed spectrophotometric method for end point determination, 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 (NH_4OAc) 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 hydrometer method (Gee and Or 2002). For microbial biomass C and N analyses, soil samples collected were thoroughly mixed and sub-sampled to obtain representative composite samples for each plot. The fresh soil samples were stored in a refrigerator at 5 ºC. Microbial biomass (C and N) were determined by chloroform fumigation extraction method (Anderson and Ingram, 1993). Microbial biomass C was calculated as follows Vance et al. (1987).

$$\text{Microbial biomass C} = (Extracted\ C_{t1} - Extracted\ C_{t0})/k_C \quad (3)$$

where: C_{t1} is the extracted C in fumigated sample, C_{t0} is the extracted C in non – fumigated sample, k_c is the factor of 0.45 used to convert organic C to C_{mic} (Jenkinson and Powlson 1976).

Microbial biomass N was determined by micro Kjeldahl method and using the formula:

$$\text{Microbial biomass N} = (\text{Extracted N}_{t1} - \text{Extracted N}_{t0})/k_N \quad (4)$$

where; N_{t1} is the extracted N in fumigated sample, N_{t0} is the extracted N in non – fumigated sample, k_N is the factor of 0.57 was used to convert the extracted organic N to N_{mic} (Jenkinson 1988).

The microbial quotient was calculated as a ratio of microbial biomass carbon (C_{mic}) to soil organic carbon (SOC) (Anderson and Domsch 1989).

Statistical analyses

Prior to the analysis, data were carefully checked for normal distribution using the Anderson–Darling test, and homogeneity of variance was assessed using Levene's test. Thereafter, data were subjected to analysis of variance (ANOVA) in GenStat statistical package 9th Edition using general treatment structure in randomized blocks (GenStat. 2007).

Results and discussion

Soil organic carbon and microbial biomass

Significant effect of cropping season was observed for soil organic carbon (SOC) content which increased by 22% in 2014 over that of 2013 cropping season. Application of compost significantly ($p < 0.001$) increased SOC content by twofold compared to plots without compost. This is most likely due to the direct addition of compost resulting in improved root biomass in the amended plots. However, numerous research reports have shown that an increase in soil carbon can be generally achieved by adding substantial quantity of organic amendment for several years (Liu et al. 2010; Rusinamhodzi et al. 2013; Zingore et al. 2015). Furthermore, other studies reported the lack of significant change in SOC content between plots receiving compost and no-compost plots in the Sahel as result of low rate of carbon sequestration in sandy soils (Bationo and Vlek 1997; Ouédraogo et al. 2001). In the current study, the large increase in SOC content observed could be attributed to the compost application method. Hill-placement of organic amendment favoured root development leading to an increase in SOC content compared to no-amended plots which recorded a decrease in SOC (Table 3). It should be noted that the SOC content reported in the current study cannot be generalized to the entire field since the sampling was restricted around the area where compost was applied. The increase in soil organic carbon with compost application has not only a potential benefit of regulating various processes underlying the supply of nutrients and the creation of a favorable environment for plant growth but also regulates various processes governing the creation of soil-based environmental services including water availability for increased rainwater use efficiency and crop yield (Bationo et al. 2007; Martínez-Blanco et al. 2013).

Soil C_{mic} was significantly ($p < 0.001$) affected by the cropping year. Soil C_{mic} increased by 25% in 2014 over that of 2013 cropping year (Table 3). A possible explanation for the increase in C_{mic} in 2014 may be the relatively higher rainfall recorded during this cropping season which adequately improved soil moisture conditions for increased root growth and soil microbial biomass. This finding is in agreement with that of Dalal and Mayer (1987) who showed that microbial biomass increased with increasing annual rainfall. Furthermore, in semiarid conditions, soil microbial biomass is generally subjected to seasonal variations due microclimate fluctuation particularly soil moisture as was the case in the current study where the two cropping years were characterized by a variation in rainfall distribution (Figure 1). Application of 1.5 t ha^{-1} and 3 t ha^{-1} of compost resulted in a significant increase in C_{mic} by a factor of 7.7 and 11, respectively relative to that of the control plot (without compost application). The increase in C_{mic} resulting from compost application is in agreement with the findings of Tejada et al. (2009) who reported an increase in C_{mic} following compost application. The increase in soil C_{mic} under compost amended plots could be attributed to the increase in soil organic carbon coupled with an increment of microbial biomass contained in the compost which stimulated the growth of indigenous soil microbiota (Garcıa-Gil et al. 2000; Katkar et al. 2011). Combined application of compost and NP fertilizer induced a synergistic effect on C_{mic}. Compost when applied in combination with NP fertilizer increased C_{mic} by a factor of 4.6 compared to NP fertilizer plots alone (Table 3) and thus signifying a synergistic outcome. These results are consistent with those of other studies which have reported increases in C_{mic} with combined application of chemical fertilizer and organic amendments (Goyal et al. 1999; Bouzaiane et al. 2007). The increase in C_{mic} with the combined application of compost and mineral fertilizer could be explained by the accumulation of organic matter, which in turn had substantial incremental effect on the soil microbial biomass. (Chakraborty et al. 2011). The current results indicate further the necessity for balanced organic matter-fertilizer application for enhancing soil microbial community.

Combined application of compost and NP fertilizer increased ($p < 0.001$) soil microbial biomass nitrogen (N_{mic}) significantly. Generally, combined application of 1.5 t ha^{-1} and 3 t ha^{-1} compost with 50% and 100% of recommended NP fertilizer respectively led to an increment in N_{mic} of 15% and 11%, respectively. There was a significant interaction ($p < 0.001$) between cropping season, compost and NP fertilizer on N_{mic}. In 2013 cropping season, application of 1.5 t ha^{-1} of compost plus NP fertilizer decreased N_{mic} compared to sole application 1.5 t ha^{-1}compost. However increasing compost rate application to 3 t ha^{-1} in combination with 50% and 100% of recommended rate of NP fertilizer increased N_{mic} by 36% and 23%, respectively (Table 3). During the 2014 cropping season, application of 3 t ha^{-1} of compost increased N_{mic} content by twofold regardless of NP fertilizer rate added. The increase in soil organic carbon as well as more root proliferation coupled with additional supply of N through compost might have been responsible for increased level of N_{mic}. The lowest N_{mic} contents were consistently recorded under sole application of NP fertilizer. Earlier studies have reported that regular applications of mineral fertilizer alone led to a decrease in the content of soil microbial biomass and compromised some soil microbial activities (Lovell and Jarvis 1998; Chakraborty et al. 2011).

Microbial quotient (Mq) represents the amount of metabolically active carbon in the total soil organic matter (Anderson and Domsch 1989). It is generally considered as a sensitive change indicator of soil organic matter quality. The microbial quotient recorded in the current study ranged from 3.6% to 15.4% in 2013 and from 1.2% to 18% in 2014. These values are particularly large compared to the range from 1 to 5% reported by number of studies (Dalal 1998; Freschet et al. 2008; Gonzalez-Quiñones et al. 2011; Sradnick et al. 2013). The larger Mq values obtained in the current study were most likely caused by the increase in microbial biomass carbon resulting from compost application and residue decomposition during the cropping season. On the other hand, an earlier study by Meyer et al. (1997) demonstrated that microbial quotient below 1% usually indicates a disturbed turnover of soil organic matter. The Mq values obtained in this study were greater than 1% under all the plots amended with compost which could be probably due to improvement in soil organic carbon content as a result of compost addition.

Table 3. Soil organic carbon and microbial biomass C, N.

		SOC (g kg^{-1})		C_{mic} (mg kg^{-1})		N_{mic} (mg kg^{-1})		Microbial quotient (%)	
Compost rate (kg ha^{-1})	% NP fertilizer recommended dose	2013	2014	2013	2014	2013	2014	2013	2014
0	0	0.63 ± 0.1	1.1 ± 0.1	27 ± 4	20 ± 2	1.2 ± 0.2	1.4 ± 0.1	4.3 ± 0.3	1.7 ± 0.3
	50	0.70 ± 0.1	1.4 ± 0.2	30 ± 3	17 ± 3	1.1 ± 0.3	2.4 ± 0.3	4.2 ± 0.3	1.2 ± 0.2
	100	0.87 ± 0.3	1.1 ± 0.3	31 ± 2	53 ± 32	1.6 ± 0.1	2.5 ± 0.6	3.6 ± 0.4	5.0 ± 1.0
1500	0	2.03 ± 0.8	2.03 ± 0.1	242 ± 7	244 ± 25	22.9 ± 4.3	39.8 ± 3.5	11.9 ± 1.1	12.0 ± 4.0
	50	2.53 ± 0.2	2.63 ± 0.3	189 ± 20	280 ± 33	13.9 ± 3.3	29.5 ± 2.6	7.5 ± 0.5	10.7 ± 1.0
	100	1.4 ± 0.2	2.83 ± 0.4	154 ± 7	233 ± 24	20.8 ± 4.1	20.7 ± 3.8	10.8 ± 2.3	8.3 ± 1.2
3000	0	1.77 ± 0.1	2.30 ± 0.1	272 ± 4	425 ± 63	22.6 ± 2.6	25.6 ± 1.8	15.4 ± 1.0	18.4 ± 2.6
	50	2.55 ± 0.3	2.5 ± 0.2	324 ± 16	336 ± 33	30.7 ± 5.3	53.4 ± 2.0	12.7 ± 1.8	13.4 ± 0.21
	100	3.03 ± 0.5	3.1 ± 0.3	320 ± 18	270 ± 15	27.9 ± 3.8	53.8 ± 3.1	10.7 ± 2.3	8.7 ± 1.0
Probability (0.05)									
Year (Y)		0.003		< 0.001		< 0.001		< 0.001	
Compost (C		< 0.001		< 0.001		< 0.001		< 0.001	
Fertilizer (F)		0.011		ns		< 0.001		ns	
Y x C		ns		ns		< 0.001		ns	
Y x F		ns		ns		< 0.001		ns	
C x F		0.027		0.002		< 0.001		< 0.001	
Y x C x F		0.04		< 0.001		< 0.001		< 0.001	
CV (%)		22.8		20.6		14.2		30.5	

SOC, organic carbon; CV, coefficient of variation; ± standard error; ns, no significant. Values reported in this table are measured around the planting hill therefore they are not representative of the whole area.

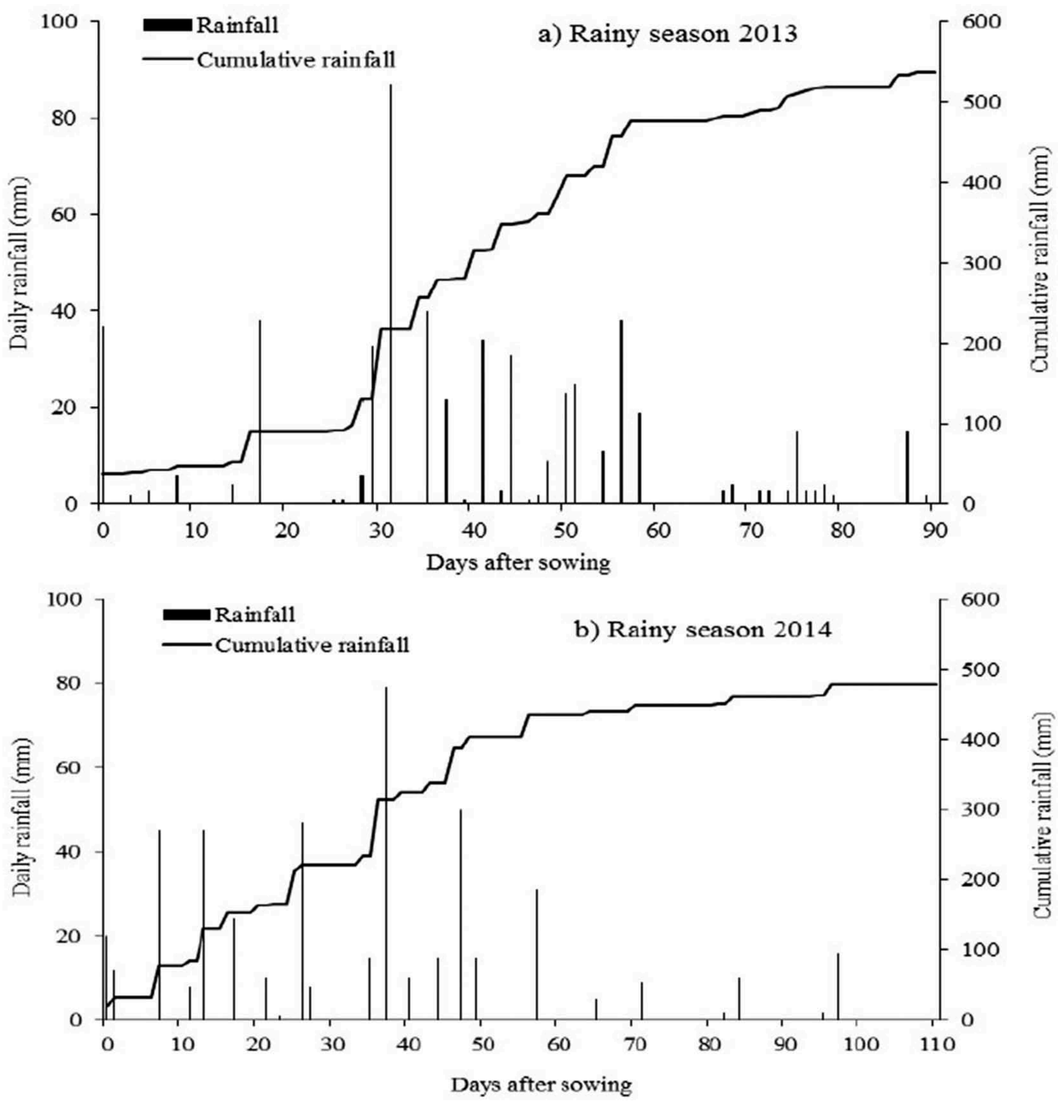

Figure 1. Rainfall distribution during the cropping season 2013 and 2014.

Millet grain and biomass yield

Millet grain and biomass yields as affected by compost and NP fertilizer application are presented in Table 4. Millet grain yields significantly differed among the cropping seasons ($p < 0.001$). Generally, millet grain yields recorded in 2014 cropping season were higher than those of 2013 cropping season. The same trend was observed in millet total biomass production with the highest production being recorded in 2014. The increase in millet yields recorded in 2014 cropping season was probably due to the residual effect of compost applied and increased soil microbial biomass during this cropping season. There was, no significant interactions between compost and NP fertilizer application on both millet grain yield and total dry matter production. However, compost application significantly ($p < 0.001$) improved millet yields. Generally, application of compost increased millet grain yield from 59% to 91% compared to that of the control plots (without amendment). There was, also a significant effect ($p < 0.001$) of NP fertilizer application on both

Table 4. Millet grain yield and total dry matter production.

Compost rate (kg ha^{-1})	% NP fertilizer recommended dose	Grain yield (kg ha^{-1}) 2013	Grain yield (kg ha^{-1}) 2014	TDM yield (kg ha^{-1}) 2013	TDM yield (kg ha^{-1}) 2014
0	0	500 ± 64	365 ± 27	1215 ± 114	1015 ± 94
	50	558 ± 43	783 ± 66	1473 ± 194	2735 ± 203
	100	853 ± 142	1131 ± 180	1670 ± 51	2989 ± 108
1500	0	770 ± 43	1082 ± 158	1874 ± 221	2287 ± 159
	50	1077 ± 262	1022 ± 108	2036 ± 218	2341 ± 173
	100	1141 ± 254	1588 ± 171	2036 ± 311	3501 ± 107
3000	0	997 ± 113	1170 ± 144	1874 ± 158	2767 ± 174
	50	1134 ± 182	1726 ± 173	1988 ± 212	3520 ± 154
	100	1269 ± 166	1758 ± 111	3003 ± 161	3755 ± 189
Probability (0.05)					
Year (Y)		< 0.001		< 0.001	
Compost (C		< 0.001		< 0.001	
Fertilizer (F)		< 0.001		< 0.001	
Y x C		ns		ns	
Y x F		ns		ns	
C x F		ns		ns	
Y x C x F		ns		ns	
CV (%)		28		26	

CV, coefficient of variation; ± standard error.

millet grain yield and total dry matter production. Furthermore, combined application of compost and NP fertilizer induced an additive-effect on millet yields in both cropping seasons. Combined application of compost along with NP fertilizer increased millet grain yields on average from 57% to 70% in 2013 and from 36% to 82% in 2014. The highest millet grain yield obtained with the combined application of 3 t ha^{-1} of compost and 100 % NP fertilizer. On the other hand, millet grain yields recorded with the combined application of compost and 50% of the recommended rate of NP fertilizer were higher than those obtained with sole application of 100% recommended application of NP fertilizer. Given that most smallholder farmers cannot afford to buy the recommended quantity of mineral fertilizer to achieve acceptable yields, farmers should be encouraged to use compost in combination with half of the recommended rate of mineral fertilizer. This is in line with earlier studies which reported the possibility of enhancing fertilizer use efficiency and reducing the amount of inorganic fertilizer required by 50% through integrated use of mineral fertilizer and organic material (Palm et al. 1997; Tilahun-Tadesse et al. 2013). The lowest millet grain yields were frequently recorded under the control plots. The total dry matter production followed the same trend. The dry matter production was also markedly higher with combined application of 3 t ha^{-1} and 100 % NP fertilizer in both cropping seasons. The improvement in millet yields with combined application of compost and mineral fertilizer could be attributed to better millet development due to increased availability of nutrients from the mineral fertilizer source and the gradual nutrient release from compost (Badar et al. 2015; Gonda et al. 2016).

Agronomic efficiency and rainwater use efficiency

The agronomic efficiency (EA) was significantly affected by the cropping seasons ($p < 0.001$). The highest N-AE and P-AE were recorded in 2014 (Table 5). Combined application of compost and NP fertilizer had a synergetic effect ($p < 0.001$) on AEs. N-AE values from combined application of compost and NP fertilizer were 3.7 and 2.3 times higher than the sum of those of sole NP fertilizer application, respectively in 2013 and 2014. The higher N-AE observed with combined application of compost and NP fertilizer can be attributed mainly to the higher N supply through combined use of compost and NP fertilizer compared with those from the sole application of NP fertiliser and compost. The values of N-AE obtained with combined application of compost and NP fertilizer mirrored the average (38 kg kg^{-1}) of N-AE reported

Table 5. Agronomic efficiency and rainwater use efficiency.

Compost rate (kg ha^{-1})	% NP fertilizer recommended dose	AE-N (kg kg^{-1}) 2013	AE-N (kg kg^{-1}) 2014	AE-P (kg kg^{-1}) 2013	AE-P (kg kg^{-1}) 2014	RUE (kg mm^{-1}) 2013	RUE (kg mm^{-1}) 2014
0	0					0.9 ± 0.04	0.7 ± 0.1
	50	4.5 ± 0.3	18.9 ± 4.4	10.3 ± 4	52.2 ± 4	1.1 ± 0.2	1.6 ± 0.1
	100	11.8 ± 2.7	21.1 ± 5.2	36.2 ± 6	37.7 ± 6	1.6 ± 0.3	2.4 ± 0.4
1500	0	51.1 ± 7.2	97.1 ± 14.4	65.8 ± 9	180.3 ± 26	1.5 ± 0.1	2.3 ± 0.3
	50	27.5 ± 5.2	24.9 ± 5.1	54.3 ± 10	48.7 ± 5	2.0 ± 0.4	2.1 ± 0.2
	100	17.8 ± 3.6	30.2 ± 4.7	36.3 ± 7	44.1 ± 4	2.1 ± 0.2	3.3 ± 0.4
3000	0	41.4 ± 9.4	55.9 ± 11.9	53.4 ± 9	86.4 ± 9	1.9 ± 0.3	2.4 ± 0.3
	50	23.5 ± 3.7	43.1 ± 6.4	48.2 ± 11	61.6 ± 7	2.1 ± 0.2	3.5 ± 0.1
	100	52.3 ± 7.1	83.1 ± 7.2	63.5 ± 7	117.3 ±	2.4 ± 0.3	3.7 ± 0.2
Probability (0.05)							
Year (Y)		< 0.001		0.001		< 0.001	
Compost (C		< 0.001		0.004		< 0.001	
Fertilizer (F)		< 0.001		< 0.001		< 0.001	
Y × C		ns		ns		ns	
Y × F		0.002		ns		ns	
C × F		< 0.001		< 0.001		ns	
Y × C × F		< 0.001		ns		ns	
CV (%)		26		31		28	

CV, coefficient of variation; ± standard error; ns, no significant.

by Vanlauwe et al. (2011) from the application of organic resources (manure or compost) in combination with N fertilizer. The P-AE values with compost application were 1.6 times much higher compared to those of the sole application of NP fertilizer. In general, N-AE and P-AE increased with reducing nutrient application rates. Generally, the AEs tended to be highest for sole application of 1.5 t ha^{-1} of compost in both cropping seasons. However, for integrated use of compost and NP fertilizer options, the highest AEs of N and P were constantly recorded with the application of 3 t ha^{-1} of compost in combination with 100% of recommended NP fertilizer (Table 5). The increase in AE resulting from combined application of compost and NP fertilizer could be explained by the high yield produced.

Rainwater use efficiency (RUE) is presented in Table 5. The RUE was significantly higher ($p < 0.001$) in 2014 cropping season which could be explained by the higher yield recorded during the cropping year. There was, an additive-effect of combined application of compost with NP fertilizer on RUE. In both cropping seasons, the highest RUE was consistently recorded when 3 t ha^{-1} of compost was applied with 100% of NP fertilizer. Generally, application of compost in combination with NP fertilizer increased RUE by 34% and 31%, respectively in 2013 and 2014 relative to that of the sole application of 100% of NP fertilizer. Several studies have reported an increment in millet water use efficiency in response to combined application of organic resource with mineral fertilizer in the Sahelian zone resulting from improved biomass production (Manyame 2006; Ibrahim et al. 2015).

Conclusion

The results of this study indicate that the application of MGD-compost in combination with NP fertilizer enhances millet yields in a low-input cropping system by increasing soil microbial biomass and thereby enhancing soil nutrient availability. In addition, this study demonstrates that alternative use of MGD-compost could serve as a suitable source of nutrient for further increasing crop yields and enhancing soil organic carbon of the Sahelian sandy soils characterized by low organic matter. Based on the level of yields recorded in this study, we recommend that smallholder farmers in the Sahelian zone of Niger apply compost at 3 t ha^{-1} (300 g hill^{-1}) in combination with 50% of NP fertilizer as this reduces chemical fertilizer investment by 50% and also increases biomass production to further build soil organic matter and conserve soil moisture and consequently reduce climate-variability effects associated with sole use of chemical fertilizer.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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