Minimizing nutrient leaching from maize production systems in northern Ghana with one-time application of multi-nutrient fertilizer briquettes

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Abstract

Nutrient losses through surface runoff and leaching from agricultural lands could have negative effects on surface water and groundwater resources in northern Ghana. Nutrient management strategies that synchronize nutrient uptake with availability will increase nutrient recovery efficiency and minimize nutrient losses to the environment. From field trials conducted at three locations in northern Ghana during the 2016 and 2017 farming seasons, we evaluated the effectiveness of one-time application of multi-nutrient fertilizer briquettes in minimizing nutrient leaching losses from maize production systems. We compared six fertilization strategies: (i) farmer practice (FP); (ii) NPK fertilizer briquettes applied at the recommended N, P, and K rates (100% briquette); (iii) 75% briquette; (iv) modified farmer practice (MFP) with granular N, P, and K sources applied at the recommended rate (100% MFP); (v) 75% MFP; and (vi) Control, with no fertilizer applied. Across all locations and both seasons, maize grain yield resulting from the treatments followed this order: 100% briquette > 75% briquette = 100% MFP > 75% MFP > FP > control. Concentrations of leachate N from the two briquette treatments were consistently similar to background levels throughout the sampling periods, with the FP resulting in the greatest leachate N concentrations, followed by its modifications. There were no significant treatment effects on leachate P and K concentrations. Therefore, for environmental sustainability, the one-time application of multi-nutrient fertilizer briquettes could be an ideal fertilizer management strategy for maize production in northern Ghana. In addition to the environmental benefit of decreased nutrient leaching, one-time application of multi-nutrient fertilizer briquettes could provide significant agronomic benefits of increased yields from increased nutrient retention in the soil and improved nutrient utilization by the maize plants.

Keywords: Agronomic efficiency; Fertilizer deep placement (FDP); Maize grain yield; Nutrient recovery efficiency; Nutrient uptake; Suction lysimeter

1. Introduction

Maize (Zea mays L.), one of the most prominent cereal crops cultivated in northern Ghana, requires large amounts of organic and inorganic fertilizers to achieve high yields (MOFA, 2011). For most crops, including maize, nutrient uptake is largest several weeks after planting (Halvorson and M Bartolo, 2014), creating a time gap between preplant fertilizer application and significant plant N uptake. Thus, it is virtually impossible to produce maize other agricultural products without nutrient losses to ground and surface waters, and/or gaseous emissions to the atmosphere Delin and Stenberg (2014). This introduces a problem for possible nutrient contamination in drinking water and represents nutrients losses for the plant. A major challenge facing agriculture in recent times is to minimize nutrients in soil reaching ground and surface waters while at least maintaining if not increasing crop productivity (Delin and Stenberg (2014).

Synchronizing nutrient fertilization with plant nutrient demand has been proposed as a best management practice to reduce nutrient leaching losses. One way to accomplish this is by applying fertilizer several weeks after corn has emerged (side-dress stage). However, application at planting is preferred by farmers due to the short window of time that is often available for field operations before plant N requirements are high, and as preplant application is less costly to apply (Shaffer and Delgado 2002). Therefore, developing fertilizer products that allows for application at planting, with minimal nutrient losses is of importance for agronomic and environmental sustainability. Currently, nutrient management strategies utilized worldwide to improve nutrient recovery efficiency include the use of slow and controlled release fertilizer types (Shoji et al. 2001), splitting N recommendations into several applications (Anjum et al. 2018), and precision agriculture (Hedley, 2015). Nitrification and urease inhibitors added to urea-based fertilizers potentially offer better synchronizing nutrient release with plant requirement. Urease inhibitors (UI) slow the rate at which urea is hydrolyzed to ammonium (NH_4^+) (Timilsena et al. 2015). By doing so, UI delay release of N until soil conditions are less likely to cause loss, which may also reduce losses via nitrate (NO_3^-) leaching. Nitrification inhibitors (NI) slow the microbial conversion of NH_4^+ to NO_3^- (Timilsena et al. 2015). Hindering the nitrification rate with a NI, NO_3^- leaching is reduced by maintaining N in the less mobile NH_4^+ form (Motavalli et al. 2008; Liu et al. 2013). Zvomuya et al. (2003) reported that coating urea with polyolefin reduced N Leaching by up to 50% in potato production system. Coating urea with polymers (Chien et al., 2009) and other materials such as neem (Azadirachta indica L) oil (Bhatt, 2012), biochar (Manikandan and Subramanian, 2013) elemental sulfur (Shivay et al., 2016), and phosphogypsum (Vashishtha et al., 2010) have all proved effective in reducing N leaching losses. Although all the N management strategies are effective in improving N use efficiency and thereby reducing leaching losses associated with application of granular/prilled urea, the cost associated with these practices make them unrealistic nutrient management strategies for resource-poor smallholder farmers in northern Ghana, which constitute > 90% of the maize producers in the region (MOFA 2011).

One practical and cost-effective nutrient management strategy smallholder farmers in northern Ghana could adapt to reduce nutrient leaching losses and improve fertilizer efficiency is the fertilizer deep placement (FDP) technology. The FDP is a farmer-friendly technology that utilizes briquetted fertilizer sources, and allows for one-time application at planting, which can minimize nutrient leaching losses, without affecting maize yield. The technology involves two elements: (i) applying physical pressure to compact granular fertilizer grades into a large-sized fertilizer particles of 1-4 grams by weight, referred to as supergranules or briquettes (Figure 1), and (ii) point placement of the briquettes ~ 10 cm away from the plants and at 7-10 cm depth near the root zone of the crop being fertilized. Through the FDP technology, the avenues for nutrient losses are reduced, thereby improving nutrient uptake efficiency (IFDC 2007, 2013, 2015). Adu-Gyamfi et al. (2019) reported that through the use of fertilizer briquettes, maize plants grown in savanna agro-ecological zones of Ghana recovered >77% for the applied fertilizer to increase maize yield by > 30% relative to split application of granular fertilizer sources. Similarly, Agyin-Birikorang et al. (2018) showed that using multi-nutrient fertilizer briquettes resulted nutrient use efficiency of >66% compared to 35% from treatments with granular/prilled fertilizer sources. Islam et al. (2011) applied fertilizer briquettes to rice produced under tidal flood conditions and observed substantial increases in fertilizer recovery, and use efficiencies relative to the traditional farmer practice of applying granular fertilizer.

Few studies have examined the effectiveness of the multi-nutrient fertilizer briquettes on upland crop production, particularly in maize systems (Agyin-Birikorang et al., 2018; Adu-Gyamfi et al., 2019). Agyin-Birikorang et al. (2018) showed that the effectiveness of the multi-nutrient fertilizer briquettes is highly dependent on weather variables, particularly soil moisture, with effectiveness being reduced under dry conditions. In contrast, Adu-Gyamfi et al. (2019) also reported that even under the savanna agro-ecological zones of Ghana, where the weather conditions are relatively dry, the multi-nutrient fertilizer briquettes were agronomically effective. More research is, therefore, needed to assess the effectiveness of the multi-nutrient fertilizer briquettes under relatively dry weather conditions for maize production systems. To our knowledge, there have been no prior field-scale studies in northern Ghana that have evaluated the environmental benefits of one-time application of the multi-nutrient fertilizer briquettes in reducing nutrient leaching losses. Due to the reduced surface of the fertilizer briquettes that results in reduced dissolution rates, and subsequently synchronizing nutrient release with uptake (IFDC 2007, 2013, 2015, Adu-Gyamfi et al., 2019), we hypothesized that one-time application of the multi-nutrient fertilizer briquettes will minimize nutrient leaching losses compared with a conventional granular/prilled fertilizer products, without sacrificing crop yields and other agronomic benefits. The overall objective of this study was, therefore, to evaluate effectiveness of a one-time application of multi-nutrient fertilizer briquettes on nutrient leaching losses from maize production systems in northern Ghana. Specific objectives were to compare the effectiveness of a one-time application of multi-nutrient fertilizer briquettes to the split application of commercial granular fertilizers on (i) maize grain yield, (ii) nutrient use efficiency, (iii) residual nutrients in soil after harvest, and (iv) nutrient leaching.

2. Materials and Methods

2.1. Experimental sites

The trials were conducted during the 2016 and 2017 farming seasons at three communities in northern Ghana: (i) Gbulung in the Northern Region (NR) of Ghana with geographical coordinates of 9°33’17.7”N 0°56’57.5”W; (ii) Saboba (9°42’12.7”N 0°18’34.7”E), also in the NR of Ghana; and (iii) Garu (10°51’52.0”N 0°10’37.0”W) in the Upper East region (UER) of Ghana. The communities were selected based on the variation in soil physico-chemical properties (Table 1), which collectively represent > 70% of the soils in northern

Ghana (Tetteh et al., 2016). These communities are primarily maize cultivation areas (MOFA 2011). The entire northern Ghana is defined by a single rainy season, which normally starts in late April and occurs for a duration of about 140-190 days (Issahaku et al. 2016). The peak rainfall period usually occurs in late August or early September. About 60% of the rainfall occurs within three months (July to September), with torrential rains creating serious drainage problems (Issahaku et al. 2016).

2.2.Production of the multi-nutrient fertilizer briquettes

The local agricultural extension fertilizer recommendation for maize is 250 kg ha^{-1} of NPK compound fertilizer (usually 15-15-15 or 17-17-17). This is usually applied basally at planting or shortly after seedling emergence, and an additional 125 kg ha^{-1} of urea is applied as a side-dressing 6 weeks after planting. This makes the actual nutrient recommendation per hectare: 100 kg N, 42.5 kg P_2O_5, and 42.5 kg K_2O. Based on this recommendation, a combination of 250 kg of NPK compound fertilizer and 125 kg of urea were thoroughly mixed for the briquetting. Pre-determined quantities of the granular fertilizer products were crushed and fed into a briquetter (fabricated in IFDC, Muscle Shoals, AL) that is equipped with two rollers that, by pressure alone, forms the materials into briquettes of uniform size. The briquettes utilized for the experiments were produced in two sizes, a 3-gram size and a 2.25-gram size, with each briquette having a final nutrient composition as follows: 26.7% N, 11.3% P_2O_5, and 11.3% K_2O.

2.3. Soil sampling and analysis

Before the experiments started, composite surface soil samples were collected from each site to characterize the initial soil conditions. Each field was divided into 16 subunits, from which a composite soil sample (formed by mixing twenty 75-mm diameter core samples) was collected from the top 0.15 m of each subunit. Air-dried soil samples (<2 mm) were analysed for the following parameters: pH, KCl-extractable ammonium-N (NH_4-N), nitrate-N (NO_3-N), organic carbon, extractable (Mehlich 3) P, exchangeable K, Ca, Mg, DTPA-extractable Zn, and hot water extractable B. Selected soil chemical characteristics of initial conditions at each site are presented in Table 1.

Similarly, after the final harvest in each growing season, soil samples were collected and analysed for N, P, and K, as described above, to determine the residual nutrients remaining in the soil and to calculate the nutrient balance for each treatment.

2.4. Treatments and field layout

The treatments for the study consisted of (i) Farmer practice (FP); (ii) NPK fertilizer briquettes (26.7% N, 11.3% P_2O_5, 11.3% K_2O) applied at the recommended N, P, and K rates (100% briquette); (iii) NPK fertilizer briquettes applied at 75% of the recommended NPK rate (75% briquette); (iv) modified farmer practice with N, P, and K applied at the recommended rate (100% MFP); (v) modified farmer practice with NPK applied at 75% of the recommended rate (75% MFP); and (vi) Control (No fertilizer applied). The farmer practice involved surface broadcasting the granular fertilizer sources applied at the recommended rate, and the modified farmer practice involved subsurface incorporation (point placement) of the granular fertilizer sources into the soil. The six treatments were arranged in a randomized complete block design (RCBD) with four replications per treatment, making a total of 24 plots (6 treatments × 4 blocks) per site. The individual plot sizes were 8m X 5m, with a 2-m wide alley between blocks. The plots were separated from each other by ridges to prevent lateral movement of water and nutrients across plots during rainfall events.

2.5. Installation of suction lysimeters

Soil water was extracted with suction lysimeters that had porous ceramic cups of 0.1 MPa air-entry pressure (Soilmoisture Equipment Corp., Santa Barbara. CA). The suction lysimeters were constructed by attaching the round-bottom, porous ceramic cup to the end of polyvinyl chloride (PVC) tubing, as described in Woodard et al. (2003). Two suction lysimeters, spaced 1.6 m apart, were installed in each plot at a depth 100 cm below the soil surface, representing the depth below the root zone to capture nutrients that the plants were unable to utilize. The suction lysimeters were installed as described in Agyin-Birikorang et al. (2011) and Zvomuya et al. (2003). The suction lysimeters were briefly installed near the center of each plot. They were installed vertically into slightly larger holes, into which about 250 mL of silica flour had been added to improve the hydraulic contact between the ceramic cup and the surrounding soil. Soil augured out during hole preparation was repacked into the hole after insertion of the suction lysimeters, and they were sealed with bentonite near the soil surface to minimize water flow along the shaft.

2.6. Planting and treatment application

At Saboba and Garu, a high yielding, medium maturing (115 days), and drought-tolerant maize hybrid (*Pan 53*) was used as the test crop in both years, and in Gbulung, a locally available open-pollinated variety (*Obatan Pa*) was used. The seeds were planted at an inter-row spacing of 80 cm and intra-row spacing of 20 cm with one plant per hill, resulting in a plant population of 62,500 plants ha^{-1}. The planting was done at the onset of the rains at the various locations (commencing in mid-June to mid-July in both years). Prior to planting, the soil was tilled, and a pre-emergence herbicide was applied, or manual weed control was done, depending on the weed situation in the field.

A systems approach was used to compare the treatments, following the procedure described in Agyin-Birikorang et al. (2018). This procedure included complete basal N application for the treatments having the briquettes and split N application for the farmer practice treatments, where one-half of the N was applied basally and the remaining one-half (second N split) was applied at the V6 stage of crop growth (~ 5-6 weeks after seedling emergence). For the farmer practice treatment (T1), both the basal fertilizer (250 NPK ha^{-1}) and the second N split application (125 kg urea ha^{-1}) were done through surface broadcast; however, for the modified farmer practice treatments (T4 and T5), pre-determined quantities of the granular fertilizers were applied per plant (point placement) by sub-surface incorporation. For the NPK briquettes applied at the recommended NPK rates (T2), two 3-gram size briquettes were applied per plant, and for the treatment applied at 0.75 rate (T3), two briquettes of the 2.25-gram size were applied per plant. The briquettes were applied immediately after seedling emergence and were placed into the soil 10 cm away from the plant and 7-10 cm deep. All other management practices, including weed, pest, and disease control, were carried out when required. Pests (particularly the fall army worm) and diseases were controlled whenever any incident was observed. At physiological maturity, the four central rows of each plot were manually harvested, de-husked, and shelled. The grains were weighed, and the moisture content was measured to determine grain yield. All grain yields were adjusted to a moisture content of 15.5 % (Yin and McClure 2013) to ensure uniform treatment comparison.

2.7. Determination of nutrient uptake

Samples of the harvested grain and straw were oven-dried, ground, and digested for the determination of N, P, and K content. Nutrient uptake was calculated as the product of total biomass (grain + straw) yield and nutrient concentrations. Nutrient uptake efficiency was computed as:

$$NUpE = \frac{Nt - Nt_{control}}{NS}$$

where NUpE = nutrient recovery efficiency (kg kg^{-1}); Nt = aboveground N, P, or K accumulation in plants from the treated plots; Nt $_{control}$ = aboveground N, P, or K accumulation in plants from the control plots; and NS = total N, P, or K supplied in fertilizer.

2.8. Extraction and analyses of soil water

Water samples (~100 mL) were collected after each rainfall event that exceeded 10 mm. We applied a suction of 40-kPa using a hand pump to collect water samples from the soil water draining through the soil at the depth of installation. Preliminary trials showed that the 40-kPa vacuum was sufficient to maintain the suction in the cup above that of the surrounding soil until the sample was extracted. After extraction, samples were placed in a cooler immediately, and samples that could not be analysed immediately were acidified (pH ~2) and kept in a refrigerator until analysis. The water samples were analysed for N, P, and K by following procedures described in the standard analytical procedures for water analysis manual (Hydrology Project 1999): inorganic N by the Cd reduction + spectrophotometric NO_2 method, orthophosphate by the ascorbic acid spectrophotometric method, and K by the flame emission photometric method.

2.9. Statistical analyses

Maize grain yield and nutrient uptake were analyzed with the analysis of variance (ANOVA) procedure, which was conducted separately per location and for each year by following the randomized complete block design and using a generalized linear mixed model (PROC GLIMMIX, SAS 9.4) (SAS Institute Inc. 2018). The fertilizer treatments were used as fixed effects in the model, while the blocks and block X fertilizers were used as random effects.

Mean separations were computed using Tukey's studentized range test with an alpha value of $P = 0.05$.

Changes in soil water nutrient concentrations over time were analyzed using the regression analysis procedure from the SAS software (SAS Institute Inc. 2018). The water nutrient concentration data showed great variation (coefficient of variation > 40%) about the mean. This variation prompted a test for the normality and homogeneity assumptions of the regression analysis procedure (Littell et al. 1996). The data were not normally distributed, and the variances were not constant. Therefore, the soil water nutrient concentration data were logarithmically transformed based on the Box-Cox transformation procedure (Box and Cox, 1964) to conform to the normality and homogeneity assumptions of the regression analysis procedure. Data were back transformed for all discussions. Treatment differences were considered significant at $P \leq 0.05$.

3. Results and Discussion

3.1 Effects of fertilizer treatments on maize grain yield

There were highly significant ($p < 0.01$) treatment effects on maize grain yields at all three locations and during the two growing seasons. In both growing seasons, the 100% briquette treatment consistently produced the greatest grain yield across all three locations (Figure 1). This was followed by the 100% modified farmer practice and the 75% briquette treatments, the 75% modified farmer practice, the farmer practice, and the control, in that order. Thus, across all three locations and in both growing seasons, maize grain yield resulting from the treatments followed this order: 100% briquette > 100% modified farmer practice =75% briquette > 75% modified farmer practice > farmer practice > control (Figure 1).

On the basis of per unit weight (kg) of fertilizer applied, the one-time application of fertilizer briquettes produced grain yields that were >14% greater than the split application of the granular fertilizer products (an increase of >120% when compared with farmer practice treatment). The greatest yields obtained with the one-time briquette application suggest that more nutrients were made available to the maize plants from the fertilizer briquettes than from the granular fertilizer sources, resulting in improved growth and development. This result is consistent with the observation of Islam et al. (2011) who reported that the application of NPK briquettes resulted in a greater increase in rice yield compared to the split-application of granular fertilizer. In a study in the Sudan savanna ecological region of Burkina Faso, Bandaogo et al. (2015) showed that irrigated-rice grain yield increased by at least 25% when urea briquettes, instead of granular urea fertilizer, was applied. Agyin-Birikorang et al. (2018) reported that fertilizer briquettes consistently produced the greatest grain yields when compared with different types of granular fertilizers, producing at least 16% more grain yields than the conventional granular fertilizer sources. The authors, thus, concluded that the multi-nutrient fertilizer briquettes could be a more efficient fertilizer for upland crop production than the conventional granular fertilizers (Agyin-Birikorang et al. 2018). Briquetting of the granular fertilizers significantly reduces the surface area on a unit mass of fertilizer compared to conventional granular fertilizers (IFDC 2007, 2013). This implies that the smaller surface area of the fertilizer briquette may have reduced the rate of dissolution of the briquette and, thus, released nutrients more slowly to somewhat match the nutrient uptake of the plant. This process could reduce nutrient losses and increase nutrient availability to the maize plants. Therefore, the increase in maize yields from the fertilizer briquette treatments could be attributed to the apparent slow-release of nutrients from the fertilizer briquettes in synchrony with the maize nutrient demand.

The method of fertilizer application also influenced the effectiveness of the granular fertilizer sources. With the sub-surface incorporation of the granular fertilizer sources (100% modified farmer practice treatment), the total above-ground biomass increased at least 110% (> 2-folds) compared to the farmer practice treatment of surface broadcasting. Even with a reduced fertilizer rate of application (25% reduction), sub-surface incorporation still produced greater (≥ 50% more) yields than the farmer practice treatment. Studies have shown that by sub-surface incorporating fertilizer, avenues for nutrient losses, such as surface runoff and volatilization losses (in case of N), are reduced, making more nutrients from the applied fertilizer available for plants (Nkebiwe et al. 2016). In similar studies, Johansson et al. (2013) reported that the yield of spring malting barley was significantly increased when fertilizer sources were incorporated into the soil rather than surface applied.

3.2 Influence of fertilization strategy on fertilizer recovery efficiency of maize

There was a highly significant fertilizer treatment effect on nutrient uptake and fertilizer recovery efficiency across all locations and in the two growing seasons. The values of the total above-ground biomass N uptake for the trial conducted in the Saboba community followed a similar pattern in the two growing seasons (Figure 2). In both years, the greatest N uptake values occurred in the 100% briquette treatments. However, the N uptake values were not statistically different from those obtained from the 75% briquette and the 100% modified farmer practice treatments. The N uptake values from the 75% modified farmer practice treatment in both years were significantly less than the two briquette treatments. Among the treatments that received fertilizer application, the least N uptake values occurred in the farmer practice treatment (Figure 2). The N uptake values from the trials conducted in the Garu and Gbulung communities followed similar patterns as that of the Saboba communities, except that in the two communities, the N uptake values for the 75% modified farmer practice treatment were not statistically different from 75% briquette and the 100% modified farmer practice treatments in both growing seasons (Figure 2).

Across all three locations and in both growing seasons, the values of P uptake followed a similar pattern. Although the greatest P uptake values consistently occurred in the 100% briquette treatments, values obtained in that treatment were not statistically different from those obtained from the 75% briquette, 100% modified farmer practice, and the 75% modified farmer practice treatments. The pattern of the P uptake values in all three locations and in both years followed the order: 100% briquette = 75% briquette = 100% modified farmer practice = 75% modified farmer practice > farmer practice > control (Figure 3). In addition, the K uptake for the trials conducted in all three locations and in both years followed a similar pattern (Figure 4). With the exception of the farmer practice and the control treatments, the K uptake values were statistically similar among the four other treatments in both years, although the greatest absolute values consistently occurred in the 100% briquette treatments. Across all locations and in both years, the least K uptake values of all the treatments that received fertilizer application occurred in the farmer practice treatment (Figure 4).

On a unit weight basis, the one-time briquette application increased N uptake by >10%, P uptake by $\geq$ 8%, and K uptake by $\geq$ 8% compared to the split application of the granular fertilizer when the fertilizer was sub-surface incorporated (modified farmer practice treatments). Compared to the surface broadcast of the fertilizer sources (farmer practice), on an equivalent fertilizer rate basis, a one-time application of the fertilizer briquettes increased N uptake by >85%, P uptake by >180%, and K uptake by >22%. These results are consistent with those of Miah et al. (2016) and Kapoor et al. (2008) who reported significant increases in N, P, and K uptake from application of fertilizer briquettes compared to conventional granular fertilizers. The increased nutrient uptake from the briquette treatments explains the increase in maize yield observed for those treatments compared to the split application of granular fertilizer. Dodermann and Fairhurst (2000) reported that there is a synergism among the uptake of N, P, and K by plants, with N availability increasing the uptake of P and K. This suggests that the increased N uptake from the fertilizer briquette treatments positively influenced the uptake of P and K.

The two briquette treatments produced the greatest fertilizer recovery efficiency across all three locations and in both years, followed by the modified farmer practice treatments and the farmer practice treatments, in that order. Within the respective briquette and the modified farmer practice treatments, the lower application rates (75% rates) showed greater nutrient recovery efficiencies. Within the briquette treatments, an average N recovery efficiency from the 75% briquette treatment was ~78%, P recovery was 43%, and K recovery was 85%. On the other hand, N recovery efficiency from the 100% briquette treatment was ~67%, 38% for P, and 78% for K. Similarly, within the modified farmer practice treatments, an average of ~64% N recovery efficiency occurred in the 75% modified farmer practice, P recovery was 36%, and K recovery was 77%, whereas for the 100% modified farmer practice, an average N recovery efficiency of ~58% was observed, 35% P recovery, and 72% K recovery. This observation is consistent with the results from the study of Adjei et al. (2000) who reported an increasing N recovery efficiency with decreasing N application rates. The authors attributed the inverse relation between fertilizer application rate and N recovery to the crops' inability to utilize all applied N at higher rates, resulting in greater N losses from the treatment receiving higher fertilizer application rates (Adjei et al. 2000). The least N recovery efficiency (with an average of <30%) occurred in the farmer practice treatments, suggesting that a substantial portion (>70%) of the applied N at the recommended rate was not utilized by the crop from this treatment. The unutilized N from the surface broadcast of granular fertilizer (farmer practice), apart from being an economic loss to the farmer, could be lost to the environment, causing environmental pollution.

3.3 Residual soil nutrient status resulting from the fertilization strategy

There were significant year and location effects on the nutrient concentrations in the soil samples that were collected after crop harvest. At the Saboba trial location, the residual soil N concentration was greatest in the 100% briquette treatment in both years. In the 2016 growing season, the N concentration value observed in the 100% briquette treatments was not significantly different from that of the 75% briquette treatment. However, in 2017, the residual N concentration value was significantly greater than that of the 75% briquette treatment. Furthermore, these values were significantly greater than the modified farmer practice treatments (Table 2). In the trials conducted in Garu, the residual soil N concentrations of the two briquette treatments were significantly greater than those of the two modified farmer practice treatments in both years, followed by the farmer practice treatment, in that order. For the trials conducted in the Gbulung community, the residual soil N concentrations due to treatment effects in the two growing seasons followed the order: 100% briquette > 75% briquette > 100% modified farmer practice > 75% modified farmer practice > farmer practice > control (Table 2). With respect to the N recovery efficiency values, it was expected that the greatest N accumulation in the soil would occur in the farmer practice treatment. However, contrary to our expectation, among the fertilizer treatments, the least residual N concentrations occurred in the farmer practice treatment (Table 2). This suggests that the applied N that was not taken up by the plants and should have accumulated in the soil did not; instead, it was lost from the soil, possibly through leaching and/or ammonia volatilization.

Across the three locations and in the two growing seasons, the residual soil P concentrations followed the same pattern, with the greatest values occurring in the 100% briquette treatment. There were no significant differences in the residual soil P concentration values among the 75% briquette, 100% modified farmer practice, 75% modified farmer practice, and the farmer practice treatments (Table 2). Since the soil used was slightly acidic, the propensity of the sum of the applied P being adsorbed in the colloidal phase was high (Chang et al. 2014), making the unutilized P remain in the soil rather than get lost from the soil, as was the case of the applied N.

The residual soil K concentrations followed the same pattern across the three locations and the two growing seasons. The greatest residual soil K concentrations occurred in the 100% briquette treatment, followed by the 75% briquette and the 100% modified farmer practice treatments. Across the three locations and in the two growing seasons, the residual soil K concentrations followed the order: 100% briquette > 75% briquette = 100% modified farmer practice > 75% modified farmer practice > farmer practice > control (Table 2).

3.4. Effects of fertilizer treatments on nutrient leaching

The measured N concentrations varied over the sampling period, showing “peaks and valleys” in both years. This could be attributed to the rainfall intensity that occurred prior to soil water sampling. Generally, more rainfall immediately before sampling results in a lower leachate N concentration measurement, which could result from a dilution of the leached N. Unfortunately, the actual volume of water that percolated through the soil at each rainfall event could not be measured, and empirical calculations based on basic meteorological data introduced numerous unjustified assumptions so that the actual mass of leached N could not be quantified. However, despite this shortcoming in the study, treatment effects on leachate N concentrations were obvious. The N concentration levels measured in the collected leachate followed a similar pattern in both years at the three locations (Figures 5, 6, and 7). Across the three locations and in both years, the leachate N concentrations of the two briquette treatments were consistently similar to the control plots throughout the sampling periods; however, the leachate N concentrations of the two briquette treatments were significantly less than the treatments that received granular fertilizer application (farmer practice and its modification treatments). On the other hand, the highest leachate N concentrations were consistently measured from the farmer practice treatments, confirming that a large portion of the applied N that should have accumulated in the soil as residual N was lost in leaching. Approximately 1.5 to 2 weeks after basal fertilizer application, high N concentrations of ~6-8 mg L^{-1} were measured from the farmer practice treatment, followed by the 100% modified farmer practice and the 75% farmer practice treatments. The N concentration values from these treatments began to decrease thereafter, until about the 7th week after the split application of urea when the leachate N concentrations began to increase. N leaching reached its peak between the 8th to 9th weeks. As previously observed during these periods, the leachate N concentrations were greatest in the farmer practice treatment, followed by the 100% modified farmer practice and the 75% modified farmer practice treatments, in that order. After the 9th week of basal fertilizer application (approximately 3 weeks of split urea application), the leachate N concentration began to decrease, until it reached the background levels at approximately the 11th week of basal fertilizer application. However, the briquette treatments maintained near constant leachate N concentrations that were comparable to the background (leachate N concentrations from the control treatment) levels. Several studies have shown that high leachate N (particularly NO_3-N) concentrations are likely to pose ecological problems by contaminating groundwater and surface water resources (Woodard et al. 2002, 2003). Thus, for environmental sustainability, a critical look into the adoption of the one-time application of the multi-nutrient fertilizer briquette is hereby recommended for maize production in the northern regions of Ghana. Apart from increasing maize yields and ensuring efficient utilization of applied fertilizers, the technology ensures tremendous reduction of N leaching associated with the current farmers' practice of surface broadcasting granular fertilizer.

At all three locations and in both years, none of the leachate sampled contained a concentration of P. The samples were either absent of P, or the P concentrations in the leachates were below the instrument's detection level (0.01 mg L^{-1}) (data not presented). The K concentrations in the leachate were minimal (< 0.1 mg L^{-1}) and did not follow any particular pattern (data not presented). As such, it could not be attributed to treatment effects since the statistical analysis did not show significant differences among treatments.

4. Summary and conclusions

Field trials were conducted during the 2016 and 2017 farming seasons at three communities in northern Ghana to evaluate nutrient leaching losses from the one-time application of multi-nutrient fertilizer briquettes for maize production. We compared the effectiveness of six fertilizer management strategies (i) farmer practice (FP); (ii) NPK fertilizer briquettes (26.7% N, 11.3% P_2O_5, 11.3% K_2O) applied at the recommended N, P, and K rates (100% briquette); (iii) NPK fertilizer briquettes applied at 75% of the recommended NPK rate (75% briquette); (iv) modified farmer practice with N, P, and K applied at the recommended rate (100%

MFP); (v) modified farmer practice with NPK applied at 75% of the recommended rate (75% MFP); and (vi) Control (no fertilizer applied). Across all three locations and in both growing seasons, maize grain yield resulting from the treatments followed this order: 100% briquette > 75% briquette = 100% MFP > 75% MFP > FP > control. Fertilizer recovery efficiency followed the order: 75% briquette > 100% briquette > 75% MFP > 100% MFP > FP. Leachate N concentrations from the two briquette treatments were consistently similar to the background levels throughout the sampling periods. The farmer practice resulted in the greatest leachate N concentrations, followed by its modifications. There were no significant treatment effects on leachate P and K concentrations. Thus, apart from increasing maize yields and ensuring efficient utilization of applied fertilizers, one-time application of the multi-nutrient fertilizer briquettes ensures a tremendous reduction of N leaching associated with the current farmers' practice of surface broadcasting granular fertilizer. From the combined results, we conclude that, for environmental sustainability, adoption of the one-time application of the multi-nutrient fertilizer briquette could be an ideal fertilizer management strategy for maize production in the northern regions of Ghana. In addition to the environmental benefit of decreased nutrient leaching, one-time application of multi-nutrient fertilizer briquettes could provide significant agronomic benefits of increased yields from increased nutrient retention in the soil and improved nutrient utilization by the maize plants.

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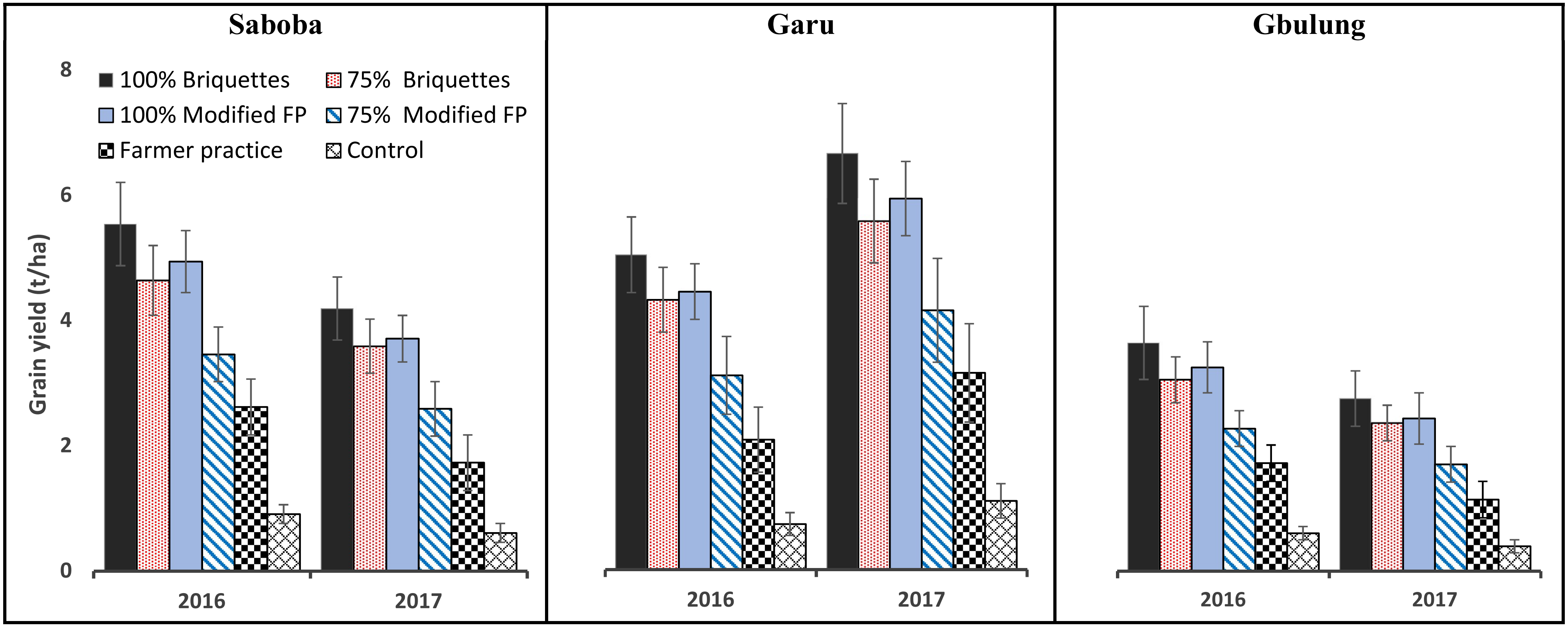

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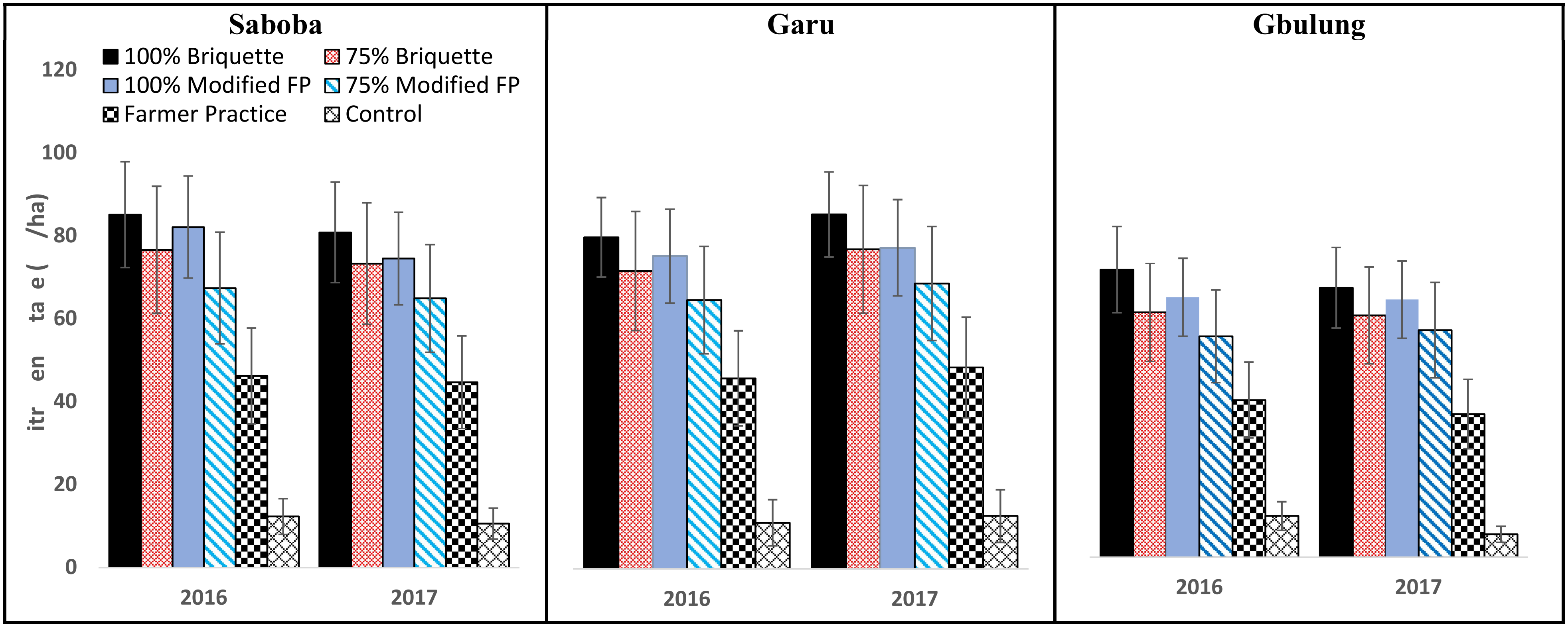

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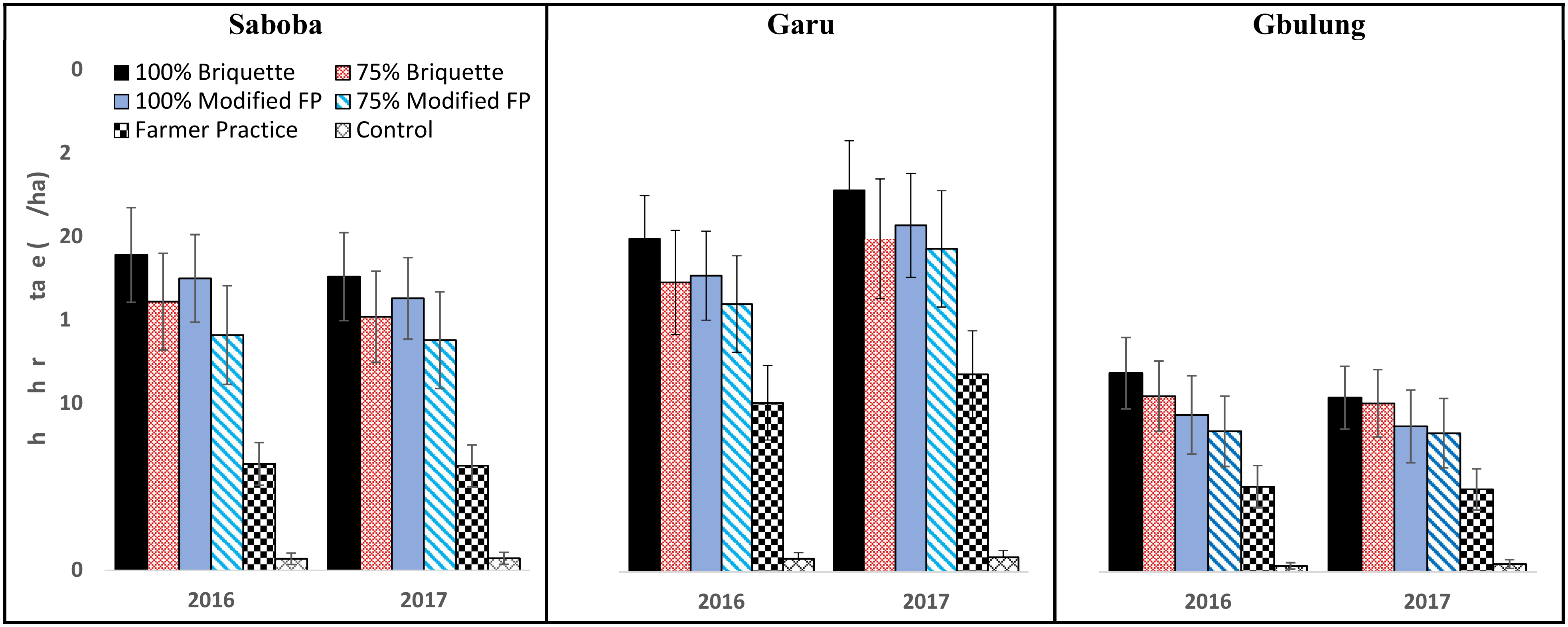

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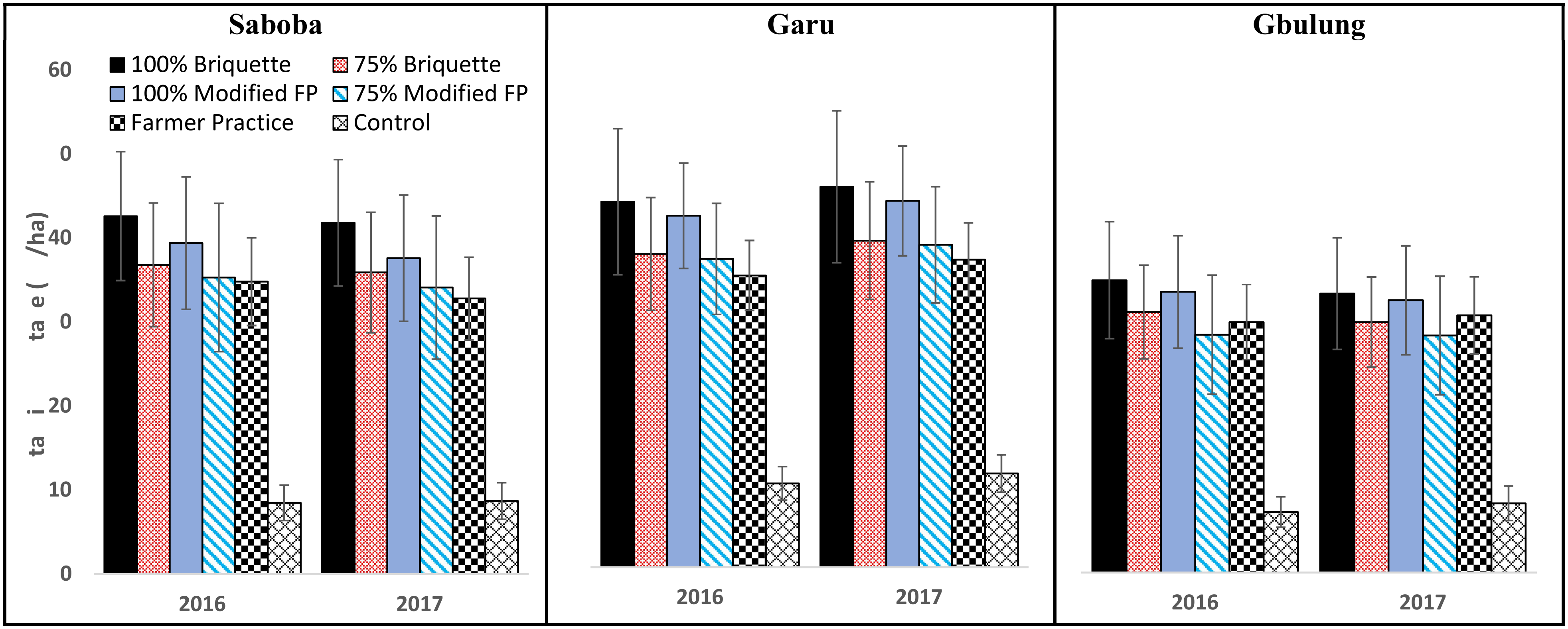

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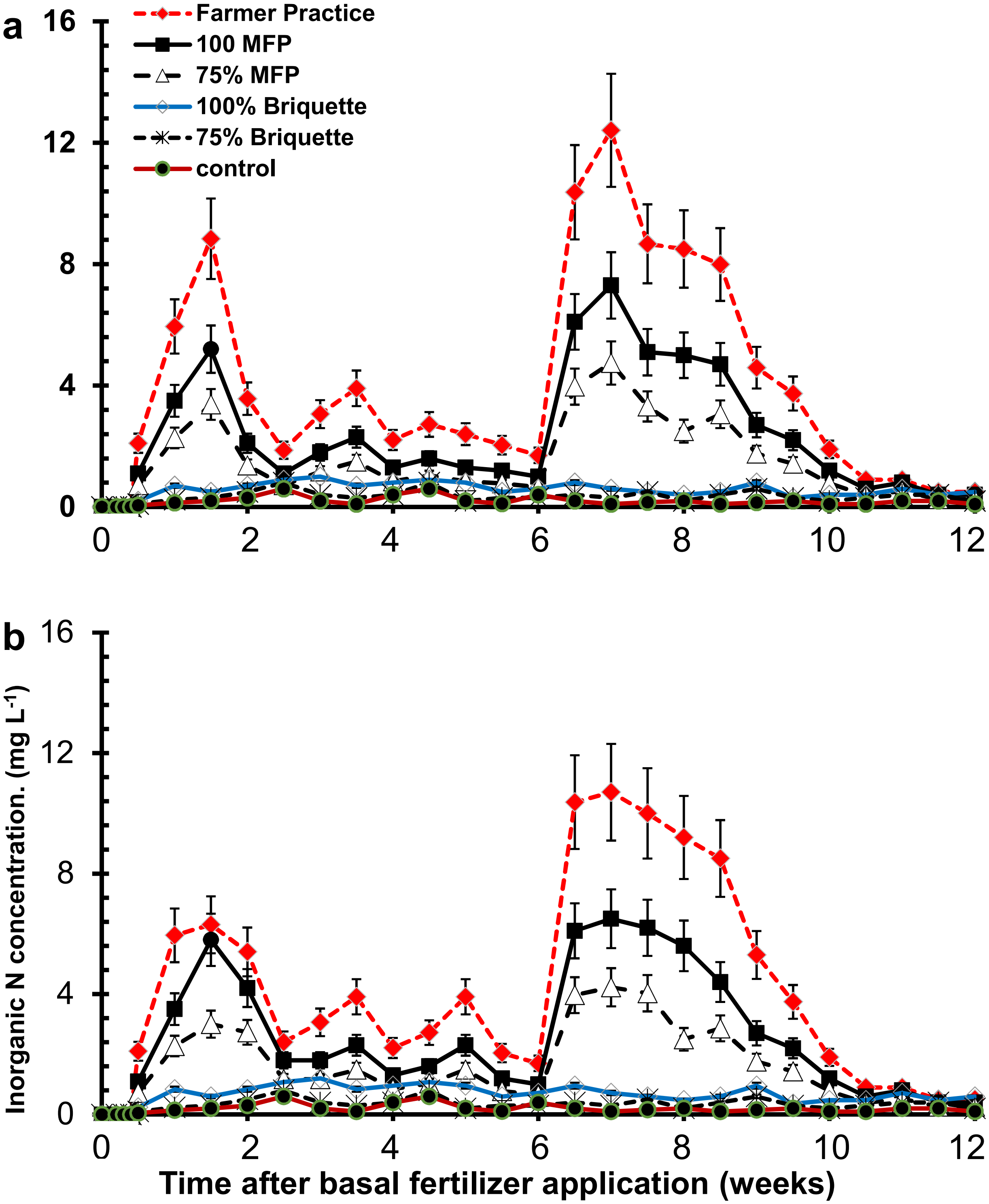


Figure 5. Average inorganic nitrogen concentration of leachate collected in the Saboba site for trial conducted (a) 2016 and (b) 2017. Error bars denote standard error of the mean. Connecting lines between points are for visual purpose only

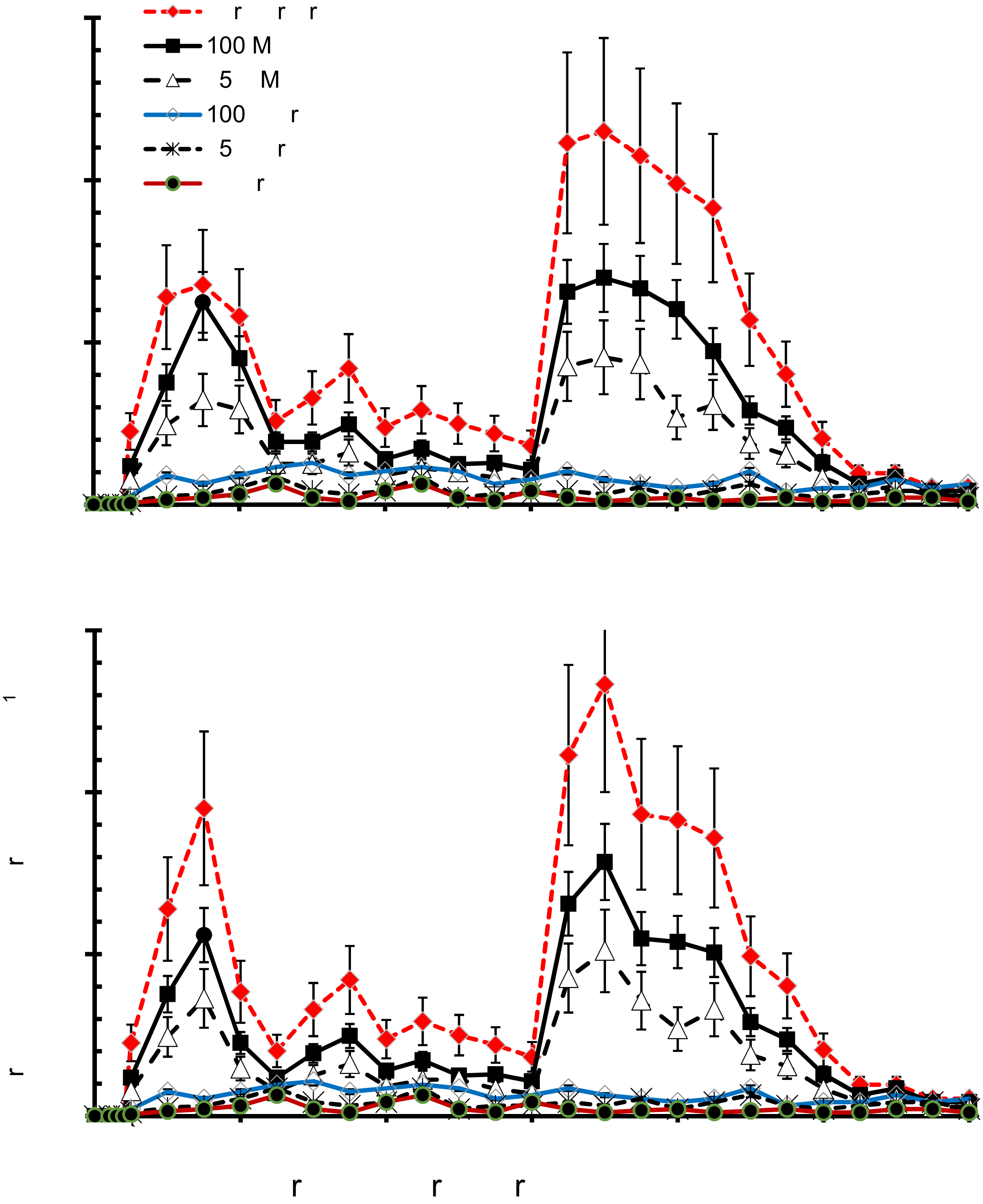


Figure 6. Average inorganic nitrogen concentration of leachate collected in the aru site for trial conducted (a) 2016 and (b) 2017. Error bars denote standard error of the mean. Connecting lines between points are for visual purpose only

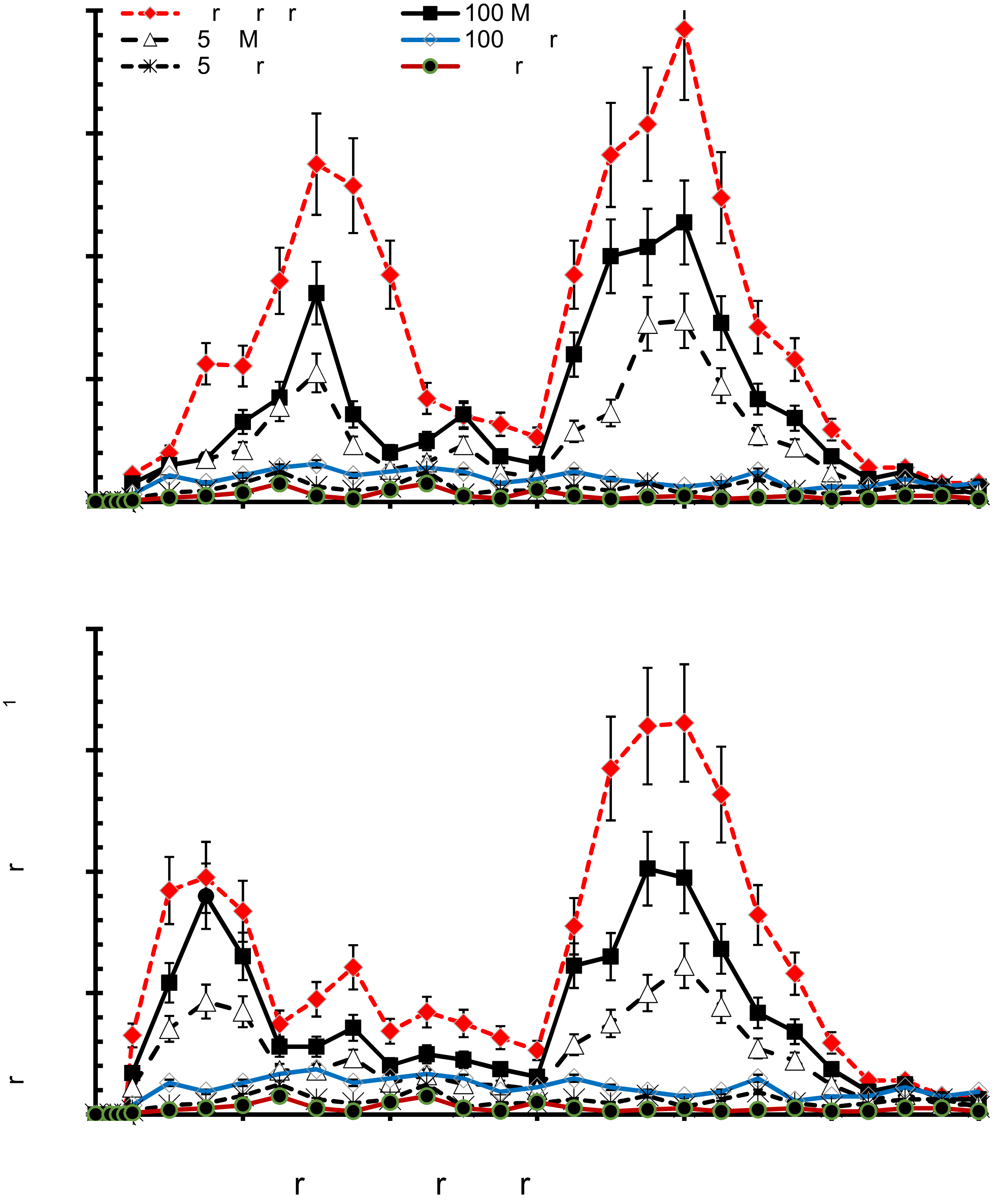


Figure 7. Average inorganic nitrogen concentration of leachate collected in the bulung site for trial conducted (a) 2016 and (b) 2017. Error bars denote standard error of the mean. Connecting lines between points are for visual purpose only

Table 1. Physico-chemical characteristics of the soils prior to the commencement of the trials at sites (Saboba, Garu, and Gbulung in northern Ghana) utilized for the study

Chemical Characteristics	**Location**		
	Saboba	Garu	Gbulung
Texture	Loam	Sandy clay loam	Loamy sand
pH	6.38 ± 0.02†	6.72 ± 0.01	5.62 ± 0.02
Organic C (g kg^{-1})	39.7 ± 5.08	49.3 ± 5.57	10.7 ± 2.02
NO_3-N (mg kg^{-1})	1.82 ± 0.24	1.34 ± 0.36	4.26 ± 1.02
NH_4-N (mg kg^{-1})	12.5 ± 2.27	17.2 ± 2.39	3.62 ± 0.76
Mehlich-3 P (mg kg^{-1})	4.21 ± 1.13	3.24 ± 0.91	3.12 ± 0.68
Exchangeable K (cmol (+) kg^{-1})	0.14 ± 0.02	0.18 ± 0.02	0.07 ± 0.01
Exchangeable Ca (cmol (+) kg^{-1})	4.28 ± 1.74	5.01 ± 1.49	1.47 ± 0.26
Exchangeable Mg (cmol (+) kg^{-1})	1.29 ± 0.19	1.54 ± 0.27	0.53 ± 0.06

† Number are mean values of 24 replicates ± standard deviation of the mean. Values are presented in 3 significant figures

Table 2. Effects of treatments on residual soil nitrogen, phosphorus, and potassium concentrations after maize harvest in Saboba, Garu, and Gbulung communities in northern Ghana during 2016 and 2017 growing seasons

Treatment	**……………………Saboba…..………………**						**………………..……Garu…………..……..……….**						**……….…………Gbulung……..………………..**					
	N concentration		**P concentration**		**N concentration**		**N concentration**		**P concentration**		**K concentration**		**N concentration**		**P concentration**		**K concentration**	
	……………………… mg kg^{-1}……………………						………………………….mg kg^{-1}…………………..………						……………………… mg kg^{-1}……………………					
	2016	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
100% Briquette	7.52a	10.9a	12.1a	22.3a	25.7a	26.5a	10.6a	11.7a	11.7a	21.2a	25.1a	34.3a	14.3a	18.6a	12.6a	16.8a	18.1a	23.6a
75% Briquette	6.88a	8.76b	9.05b	17.1b	21.4b	22.2b	9.65a	10.8a	8.80b	16.5b	21.0b	30.4ab	11.2b	12.7b	7.22b	10.2b	14.4b	20.6b
100% Modified Farmer Practice	4.73b	6.26c	8.39b	16.5b	18.8b	20.6b	6.80b	7.84b	8.19b	17.9b	21.4b	30.7ab	9.18c	8.66c	8.87b	10.9b	15.3b	21.1b
75% Modified Farmer Practice	3.65c	5.56c	7.85b	15.8b	12.8c	18.0c	4.11c	5.16c	7.60b	16.3b	19.1c	23.5c	4.89d	6.20d	6.01b	8.02c	10.4c	19.8c
Farmer Practice	3.42c	3.11d	7.71b	15.9b	9.17d	15.3d	3.57c	3.01d	7.55b	15.9b	13.9d	18.4d	3.71d	3.46d	5.81b	6.82b	8.76d	14.5d
Control	2.65d	1.79e	2.77c	1.44c	8.82e	6.18e	3.43c	2.32d	2.13c	1.87c	8.1e	6.73e	1.46e	0.99e	2.05c	1.80c	10.9e	6.16e

† Numbers are mean values of four replicates, presented in 3 significant figures

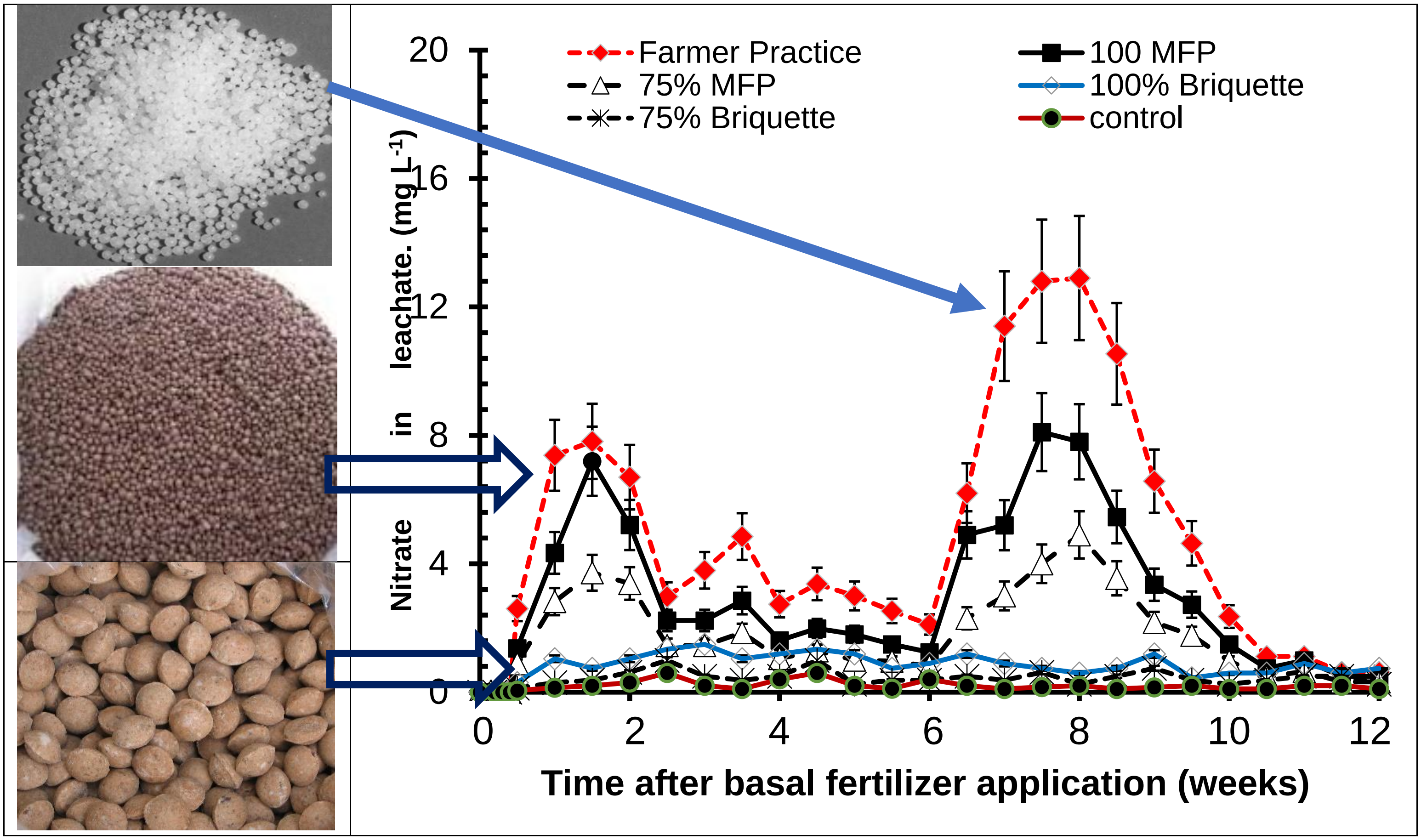
‡ Numbers in each column followed by the same letter are not significantly different (P > 0.05)

Table 3. Nutrient recovery efficiencies as influenced by different fertilizer treatments on maize grown in Saboba, Garu, and Gbulung communities in northern Ghana during 2016 and 2017 growing seasons

Treatment	**……………………Saboba…..………………**						**……………..……Garu………..……….**						**……………..Gbulung……..……….**					
	N recovery efficiency		P recovery efficiency		K recovery efficiency		N recovery efficiency		P recovery efficiency		K recovery efficiency		N recovery efficiency		P recovery efficiency		K recovery efficiency	
	---------------------------------% -------------------------						--------------------------------% --------------------------						-------------------------------% ----------------------------					
	2016	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
100% Briquette	72.8b	70.2b	42.8b	39.7b	80.3b	77.9a	68.6b	72.5bc	45.0b	51.6bc	80.0a	81.4a	59.9ab	60.0bc	31.5b	27.2b	65.1b	58.9b
75% Briquette	85.6a	83.6a	48.3a	45.4a	88.8a	85.4a	80.7a	85.5a	51.8a	59.7a	86.9a	88.2a	66.0a	71.0a	37.0a	35.0a	74.9a	67.9a
100% Modified Farmer Practice	69.8b	63.9c	39.6b	36.7b	72.8c	68.0b	64.1b	64.5c	39.8c	46.7c	76.0a	77.4a	53.2b	57.1c	24.7c	22.5c	61.8bc	57.0b
75% Modified Farmer Practice	73.7b	72.4b	42.1b	41.0ab	84.1ab	79.7a	71.3b	74.5b	47.7ab	57.8ab	85.0a	86.6a	58.3ab	66.2ab	29.3b	28.5b	66.4ab	62.9ab
Farmer Practice	33.9c	34.1d	13.4c	13.1c	61.9d	56.3c	34.7c	35.7d	21.9d	25.7d	59.1b	60.7b	28.2c	29.3d	12.9d	12.2d	53.3c	52.8c

† Numbers are mean values of four replicates, presented in 3 significant figures

‡ Numbers in each column followed by the same letter are not significantly different ($P > 0.05$)


Farmer Practice
100 MFP
75% MFP
100% Briquette
75% Briquette
control
Nitrate in leachate. (mg L^{-1})
0
4
8
12
16
20
0
2
4
6
8
10
12
Time after basal fertilizer application (weeks)