frontiers | Frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 29 April 2022
doi: 10.3389/fsufs.2022.796878

Nutrient Inputs for Rehabilitation of Non-responsive Soils in the Guinea and Sudan Savannah Agroecological Zones of Ghana: Impact on Grain Yield and Soil Quality

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Studies have shown that the continuous application of N, P, and K fertilizers has led to the depletion of secondary and micronutrients, which have become limiting nutrients hindering crop growth and yield. An on-farm trial was conducted to determine the effect of site-specific nutrient fertilizers and compost on soybean yield, phosphorus use efficiency, and soil properties, at Nyong Guma, Serekpere, Daffiama Saapare, and Naaga in northern Ghana. Nine (9) treatments (3 rates of mineral fertilizer × 3 rates of FertiSoil) were applied in a factorial combination arranged in randomized complete block design with three replications. On average, the soybean grain yield increased significantly with the combined application of FertiSoil and mineral fertilizer at full rates at Nyong Guma, Serekpere, and Naaga from $<1{,}000$ kg ha^{-1} to $>1{,}500$ kg ha^{-1}. The co-application of 50% recommended rate (RR) of mineral fertilizer and 5 t ha^{-1} FertiSoil increased soybean grain yield by over 250% at Daffiama Saapare. The application of 50% RR mineral fertilizer significantly increased phosphorus use efficiency by 5–55% compared to its combination with FertiSoil or FertiSoil alone at different rates across locations. Incorporation of 5 t ha^{-1} FertiSoil and 100% RR mineral fertilizer significantly increased exchangeable K, Ca, and Mg, and microbial C and P by 0.33, 2.84, 0.56 cmol$_{(+)}$ kg^{-1} and 102.7, 33.37 mg kg^{-1}, respectively, at Serekpere. The combined application of 5 t ha^{-1} FertiSoil and 50% RR mineral fertilizer relatively increased soil organic C (42%) and available P (12%) at Naaga. The soil quality index revealed that the addition of 5 t ha^{-1} FertiSoil to 100% RR mineral fertilizer was the most sustainable nutrient management option across the study sites. Sole mineral fertilizer treatments at 50% RR were the most profitable in all the study locations ranging from value cost ratio (VCR) of 2.7–7.6. The application of limiting nutrients and organic amendments serves as an efficient nutrient management option to improve soil health, crop production and economic profitability on smallholder non-responsive soils.

Keywords: compost, macronutrients, micronutrients, phosphorus use efficiency, soil quality, soil health

Edited by:
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Specialty section:
This article was submitted to Agroecology and Ecosystem Services, a section of the journal Frontiers in Sustainable Food Systems

Received: *27 October 2021*
Accepted: *29 March 2022*
Published: *29 April 2022*

Citation:
Asei R, Abaidoo RC, Opoku A and Adjei-Nsiah S (2022) Nutrient Inputs for Rehabilitation of Non-responsive Soils in the Guinea and Sudan Savannah Agroecological Zones of Ghana: Impact on Grain Yield and Soil Quality. Front. Sustain. Food Syst. 6:796878. doi: 10.3389/fsufs.2022.796878

INTRODUCTION

The global population is projected to rise to 10 billion by the end of this century, while Africa's population is expected to double in the 50 years ahead (De la Croix and Gobbi, 2022).

The growing demand for food by the rising population would require greater utilization of natural resources like water, land, and nutrients to increase crop production (Tilman et al., 2011). In sub-Saharan Africa (SSA), the yields of food security crops such as maize and beans are <1 t ha^{-1} which are far below the potential yields. The decrease in yield is attributed primarily to the soil fertility loss in smallholder farms (Sánchez, 2010). The use of primary macronutrient fertilizers, N, P, and K (briefly, NPK) has been the focus of many soil fertility interventions in SSA over the decades in increasing yields and improving the livelihoods of smallholder farmers. Regardless of the positive response of crops to NPK fertilizers reported in several studies, the evidence of poor or lack of crop response to NPK fertilizers is also abundant (Abebe et al., 2015; Kihara et al., 2016; Roobroeck et al., 2021). Soil non-responsiveness is influenced by chemical, physical, and biological factors either singularly or in combination (Vanlauwe et al., 2012). The non-responsive soils are increasingly becoming widespread and they represent majority of smallholder farmers' fields in SSA (Tittonell and Giller, 2013) and the resulting agronomic and economic efficiency of nutrient inputs on such soils are very poor (Kurwakumire et al., 2014).

Tittonell and Giller (2013) reported a mean loss of 5.2 t ha^{-1} of maize grain yield in five East African countries due to poor crop response to NPK fertilizers. The key factors identified for the lack of response were loss of soil organic matter and poor agronomic managements. A dissemination project established by N2Africa in northern Ghana to test the response of legumes to P fertilizers and/or rhizobia inoculant in 2011–2012 identified about 30% of the experimental fields to be non-responsive (Woomer et al., 2014).

Nurudeen et al. (2015) also reported the application of P and K fertilizers showed no significant effect on maize grain yield and profitability in Sudan savanna agroecological zone of Ghana due to poor soil fertility. A study by Ronner et al. (2016) also found negative responses of soybean to P fertilizer application and cited multiple nutrient deficiencies and shallow depth as explanatory variables for the lack of crop response.

The continuous use of NPK fertilizers in intensive cropping systems with less usage of organic inputs contributes to rapid depletion of secondary and micronutrients in soils (Das and Mandal, 2015). Several studies have reiterated and confirmed the importance of the secondary and micronutrients on crop production (Nziguheba et al., 2009; Afolabi et al., 2014; Asei et al., 2015). In India, for instance, deficiencies of sulphur (S), boron (B), and zinc (Zn) led to crop yield stagnation for 10 years (Sahrawat et al., 2010). Agyin-Birikorang et al. (2022) in a field trial illustrated that the omission of S, Zn, and B reduced maize grain yield by an average of ≈34, 28, and 14%, respectively, in northern Ghana. A review by Bua et al. 2020 on the yield responses of maize to fertilizers in Ghana reported average yield gains of 1.5, 0.9, and 0.4 t ha^{-1} to NPK and S fertilizer in three agroecologies. This means that applying secondary, micronutrients, and organic fertilizers to fields where crops are non-responsive to NPK fertilizers has the potential to increase yields beyond what can be achieved with only NPK fertilizers (Kihara et al., 2020).

However, the research on the potential impact of secondary and micronutrients on crop productivity is limited and scattered in SSA despite their influence on crop production (Kihara et al., 2017). Furthermore, the majority of soil fertility studies are not based on the site-specific fertilizer recommendations but are based on blanket fertilizer recommendations and may result in under or over fertilization or improper balance of nutrients in farmers' fields (Richards et al., 2015).

The lack of crop response to NPK fertilizers have been ascribed to multiple nutrient deficiencies, low organic matter, poor physical factors among others (Nziguheba et al., 2009; Kihara et al., 2016).

Studies on the relative contribution of these factors to the lack of crop response to NPK fertilizers are lacking. There is also a dearth of information on the influence of the site-specific fertilizer application and organic amendment on soil quality indicators. Understanding the conditions of soil and crop non-responsiveness to macronutrient fertilizers is imperative to bridge the yield gap and achieve the full potential of crops and soils for food security and agricultural sustainability. The aim of this research was to evaluate the effect of mineral fertilizers and/or compost on soybean grain yield, some soil properties, and their economic benefit on some identified non-responsive soils.

MATERIALS AND METHODS

Site Description

An agronomic trial for assessing crop response to different rates of mineral fertilizer and compost was established in the Northern (Nyong Guma), Upper West (Serekpere and Daffiama-Sapaare), and Upper East (Naaga) regions of Ghana (**Table 1**) during the 2016 and 2017 cropping seasons. These four study sites were identified as non-responsive soils by an N2Africa project "putting nitrogen fixation to work for smallholder farmers in Africa" through an agronomic trial in northern Ghana (Woomer et al., 2014). The Northern region falls within the Guinea savannah and the Upper East is of the Sudan savannah. The Upper West region is sub-divided into two agro–ecological zones, the southern part being the Guinea savannah and the northern and north eastern part being Sudan savannah based on their rainfall pattern. The zone has a unimodal rainfall pattern which starts from May to October. Due to this, the region has a single growing season. The mean annual rainfall is between 1,000 and 1,100 mm with a growing period of 180–200 and 150–160 days for the Guinea and Sudan savannahs, respectively (MoFA, 2013).

Field Experimentation and Treatment Combination

The trial consisted of 27 plots; each plot measured 4 m × 4 m separated by a 1 m central buffer between plots and a buffer row in all the experimental sites. A total of nine treatment combinations (three levels of mineral fertilizer and three levels

TABLE 1 | The GPS coordinates, nutrient deficiencies, and soil type of experimental sites.

Site	Latitude	Longitude	Limiting nutrients	Soil type
Nyong Guma	N09°52.505′	W000°39.173′	P, K, Zn, B	Dystric Plinthosols
Serekpere	N 10°17.911′	W002°36.153′	P, K, Mg, S	Gleyic Lixisols
Dafiama Sapaare	N 10°24.828′	W002°32.906′	P, K, Mg, S, Ca	Lithic Leptosols
Naaga	N 10°38.066′	W 001°02.072′	P, K, Mg, S, Zn, B	Dystric Leptosols

of compost) were applied in a factorial experiment arranged in randomized complete block design replicated three times. The mineral nutrients applied were based on the limiting nutrients identified through a nutrient omission trial in a previous study (Asei et al., 2021). Two seeds of soybean variety "Jenguma" (TGx series) were planted per hole at 75 cm row width and 10 cm hill space. Weeding of the fields was done as and when necessary. The seeds were inoculated with 5 g of rhizobia inoculant (Nodumax) before planting. Mineral fertilizers were applied in bands at a rate of 30 kg P ha^{-1} (TSP); 20 kg K ha^{-1} (MOP); 2.5 and 0.5 kg ha^{-1} for Mg and S, respectively ($MgSO_4$). The calcium sulfate ($CaSO_4$) was applied at a rate of 15 kg Ca ha^{-1}, $ZnSO_2$ at a rate of 2.5 kg Zn ha^{-1}, and Fertibor at a rate of 0.5 kg B ha^{-1} at 2 weeks after sowing. The compost was broadcasted and incorporated into the soil by shallow tillage before planting. FertiSoil (commercial compost) was applied at a rate of 5 t ha^{-1} to the respective plots and mixed with the top–soil prior to planting. Both nutrient inputs were applied at 50 and 100% RR.

Soil Sample and FertiSoil Analyses

Samples of soil were taken from a 0–15 cm depth per field following the "Y frame sampling method" using an auger at the beginning and end of the 2-year field trial. Soil samples were collected into zip bags and stored at 4°C prior to laboratory analyses at the soil science laboratory, Department of Crop and Soil Sciences, Kwame Nkrumah University of Science and Technology. The soil texture was determined by the hydrometer method, pH (1:2.5 soil: water ratio), total N was analyzed by the macro Kjeldahl digestion and distillation method (Bremner, 1982), available P by the Bray 1 method (Olsen and Sommers, 1982). The modified Walkley and Black procedure as outlined by Nelson and Sommers (1996) was used to measure organic carbon content, exchangeable K, Ca, and Mg were determined in 1 M ammonium acetate (NH_4OAc) solution (Black, 1986). Bulk density (ρ_b) was measured by core method (Blake and Hartge, 1986) and aggregate stability using the wet sieving technique (Kemper and Rosenau, 1986). The microbial biomass carbon (C_{mic}), microbial nitrogen (N_{mic}) and microbial phosphorus (P_{mic}) were determined according to the fumigation extraction procedure (Anderson and Ingram, 1993). The lignin and polyphenol contents of the compost were determined by the acid detergent fiber (ADF) method described by Van Soest and Wine (1968) and Folin–Denis method (Anderson and Ingram, 1993), respectively (**Table 2**).

Data Collection

At physiological maturity stage, the seed yield of soybean plants were harvested, air-dried, threshed, and winnowed. The dry weights for each plot were then determined and used to estimate the grain yield on per hectare basis.

TABLE 2 | Chemical properties of FertiSoil used in study.

Parameter	FertiSoil		
	2016	2017	Average
Organic carbon (%)	37.85	39.26	38.56
Total nitrogen (%)	2.58	3.20	2.89
Total phosphorus (%)	1.09	1.53	1.31
Total potassium (%)	2.42	1.90	2.16
C:N ratio	14.67	12.27	13.47
Lignin content	5.40	6.50	5.95
Polyphenol content (%)	0.70	0.67	0.65

The phosphorus use efficiency (PUE) for each nutrient management option was calculated using the following equations as described by Syers et al. 2008:

$$PUE\,(\%) = \frac{Up\ -\ Uo}{Fp}\ \times 100 \tag{1}$$

where U_p refers to P uptake by crops in the fertilized P plots (kg ha^{-1}), U_o is P uptake in the control plot (kg ha^{-1}) and F_p is the total amount of P applied (kg ha^{-1}).

Soil Quality Index

To evaluate the effect of nutrient management options on soil quality, a soil quality index (SQI) was determined. The minimum data set (MDS) of soil parameters used for developing the SQI were pH; organic C; total N; available P; exchangeable cations (K, Ca, and Mg); microbial C, N, and P; bulk density; and aggregate stability (**Table 3**). The soil parameters significantly affected by the nutrient management options were used in the MDS for each site. The simple additive approach described by Amacher et al. (2007) was followed to model the SQI based on the data obtained from this research. Threshold values were established for each soil parameter according to Amacher et al. (2007) and Mukherjee and Lal (2014). The individual index values for all the soil physico–chemical and biological properties were then summed to obtain a total SQI:

$$Total\ SQI\ = \sum Individual\ soil\ parameter\ index\ values \tag{2}$$

The total SQI for the soil properties was calculated as follows:

TABLE 3 | Selected soil quality indicators and scores.

Parameter	Soil quality indicator	Scoring function
Physical	Bulk density (g cm^{-3})	Less is better
	Aggregate stability	More is better
Chemical	pH	Optimum is better
	Organic C (%)	More is better
	Total N (%)	More is better
	Available P (mg kg^{-1})	More is better
	Exch. K [$cmol_{(+)}$ kg^{-1}]	More is better
	Exch. Ca [$cmol_{(+)}$ kg^{-1}]	More is better
	Exch. Mg [$cmol_{(+)}$ kg^{-1}]	More is better
Biological	Microbial C (mg kg^{-1})	More is better
	Microbial N (mg kg^{-1})	More is better
	Microbial P (mg kg^{-1})	More is better

$$SQI \ = \left[\sum SQI \ - \ (SQI)_{\min}\right] / \left[(SQI)_{\max} \ - \ (SQI)_{\min}\right] \quad (3)$$

where $(SQI)_{min}$ is the minimum value of SQI and $(SQI)_{max}$ is the maximum value of SQI from the total dataset.

Economic Analysis

Using the value cost ratio (VCR) as an economic index, the economic viability of the various nutrient management options was evaluated. The variables used in the economic analysis were the cost of fertilizer inputs applied per hectare and the income of marketable soybean grain yield at farm gate price. The fertilizer inputs per hectare cost for Nyong Guma and Naaga were USD39, and for Serekpere and Daffiama Saapare, it cost USD25 in the first season. In the second season, the fertilizer inputs per hectare cost were USD40 for Nyong Guma, USD27 for Serekpere and Daffiama Saapare and USD41 for Naaga. The FertiSoil price per hectare were USD394 and USD478 in the first and second seasons, respectively, for all the sites. The farm gate prices for a 100-kg soybean in the first and second seasons were USD31 and USD34, respectively. The exchange rates used were GHc3.8 to USD1 in the first season and GHc4.2 to USD1 in the second season.

The VCR cost ratio was estimated as follows:

$$VCR = \frac{(YMF:FS:MF + FS \ - \ YC)\ PG}{Q\ MF:FS:MF + FS \ \times \ PQ} \quad (4)$$

where $Y_{MF:FS:MF+FS}$ is the grain yield from mineral fertilizer, compost, and combination of mineral fertilizer and FertiSoil plots at different rates, Y_C is the grain yield from control plots, P_G is the unit price of grains, $Q_{MF:FS:MF+FS}$ is the quantity of mineral fertilizer or FertiSoil or combination of mineral fertilizer and FertiSoil applied, and P_Q is the unit price of inputs incorporation.

Statistical Analyses

The linear mixed effects model was fitted using lme4 package (Bates et al., 2018) of R based on the following equation:

$$yijkl = ci + fj + cfij + lk + b\left(k\right) l \quad (5)$$

where y_{ijjk} is the observation in FertiSoil i combined with fertilizer j in replication l nested within location k; c_i is the effect of FertiSoil i; f_j is the effect of fertilizer j, c_{fij} is the effect of the interaction between FertiSoil i and fertilizer j; l_k is the effect of location k; and $b_{(k)l}$ is the effect of the replication l nested within location k.

All effects of the model were regarded as fixed except location, year, and replication. The analysis of variance (ANOVA) was performed on the soil quality data with 5% level of significance using Tukey HSD test in JMP version 14 (Carver, 2019).

RESULTS

Soil Physical and Chemical Characterization

Table 4 shows the results of the preliminary soil characteristics of the experimental sites. The soils in the study locations were inherently moderately acidic except those from Nyong Guma, which was slightly acidic. Generally, the soil organic carbon C (<1%) and total nitrogen N (<0.1%) were very low in all the sites. The available P was low at Daffiama Saapare and Naaga (<5) while Nyong Guma and Serekpere were moderate; however, these values were below the critical level (15 mg kg^{-1}) for soybean production (Staton, 2014). The exchangeable K and Ca were moderate across the study area and Mg low (<1 $cmol_{(+)}$ kg^{-1}). The ratings of soil chemical properties were based on the classification by Landon (2014). The textural class of Nyong Guma was sandy loam, sandy at Serekpere and Daffiama Saapare, and loamy sand at Naaga.

Soybean Response to Mineral Fertilizer and Organic Amendment

Significant differences ($p \leq 0.05$) were observed among the different rates of nutrient applications across locations and cropping seasons (**Figures 1**, **2**). In 2016 cropping season, the application of 5 t ha^{-1} FertiSoil and 100% RR mineral fertilizer produced higher grain yields of 1,095 and 1,273 kg ha^{-1}, respectively, at Nyong Guma (**Figure 1**). The combined application of half and full rates of FertiSoil with 100% RR mineral fertilizer increased grain yield by over 1,000 kg ha^{-1} compared to the control at Serekpere. An increase of over 600 kg ha^{-1} in grain yield was observed with sole 100% RR mineral fertilizer and combined 2.5 t ha^{-1} FertiSoil and 50% RR mineral fertilizer applications at Daffiama Saapare. The combined application of FertiSoil and mineral fertilizer at half rates gave the highest soybean grain yield of 1,444 kg ha^{-1} at Naaga (**Figure 1**).

For the 2017 cropping season, the co-application of FertiSoil and mineral fertilizer at different rates and sole FertiSoil at

TABLE 4 | Soil physical and chemical properties of study sites.

Parameter	Nyong Guma	Serekpere	Daffiama-Sapaare	Naaga
pH (1:2.5 H_2O)	6.28 ± 0.04	5.72 ± 0.04	5.50 ± 0.02	5.60 ± 0.12
Organic carbon (%)	0.76 ± 0.07	0.49 ± 0.03	0.31 ± 0.04	0.50 ± 0.04
Total nitrogen (%)	0.05 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
Available phosphorus (mg kg^{-1})	6.06 ± 0.04	7.73 ± 0.08	3.63 ± 0.09	4.46 ± 0.11
Exchangeable K ($cmol_{(+)}$ kg^{-1})	0.03 ± 0.01	0.03 ± 0.02	0.02 ± 0.01	0.02 ± 0.02
Exchangeable Ca ($cmol_{(+)}$ kg^{-1})	4.14 ± 0.14	2.20 ± 0.45	1.92 ± 0.20	3.54 ± 0.30
Exchangeable Mg ($cmol_{(+)}$ kg^{-1})	0.72 ± 0.16	0.28 ± 0.12	0.08 ± 0.03	0.40 ± 0.20
Exchangeable acidity (Al + H) ($cmol_{(+)}$ kg^{-1})	0.35 ± 0.02	0.85 ± 0.04	0.90 ± 0.10	0.60 ± 0.04
Al ($cmol_{(+)}$ kg^{-1})	0.19 ± 0.00	0.42 ± 0.00	0.57 ± 0.05	0.41 ± 0.01
Sand (%)	72.96 ± 4.44	88.88 ± 3.33	93.04 ± 2.58	76.96 ± 5.96
Clay (%)	6.92 ± 1.44	6.20 ± 0.34	5.64 ± 1.10	6.20 ± 0.24
Silt (%)	20.12 ± 0.12	4.92 ± 1.11	1.32 ± 0.43	16.84 ± 0.89
Textural class	Sandy loam	Sand	Sand	Loamy sand

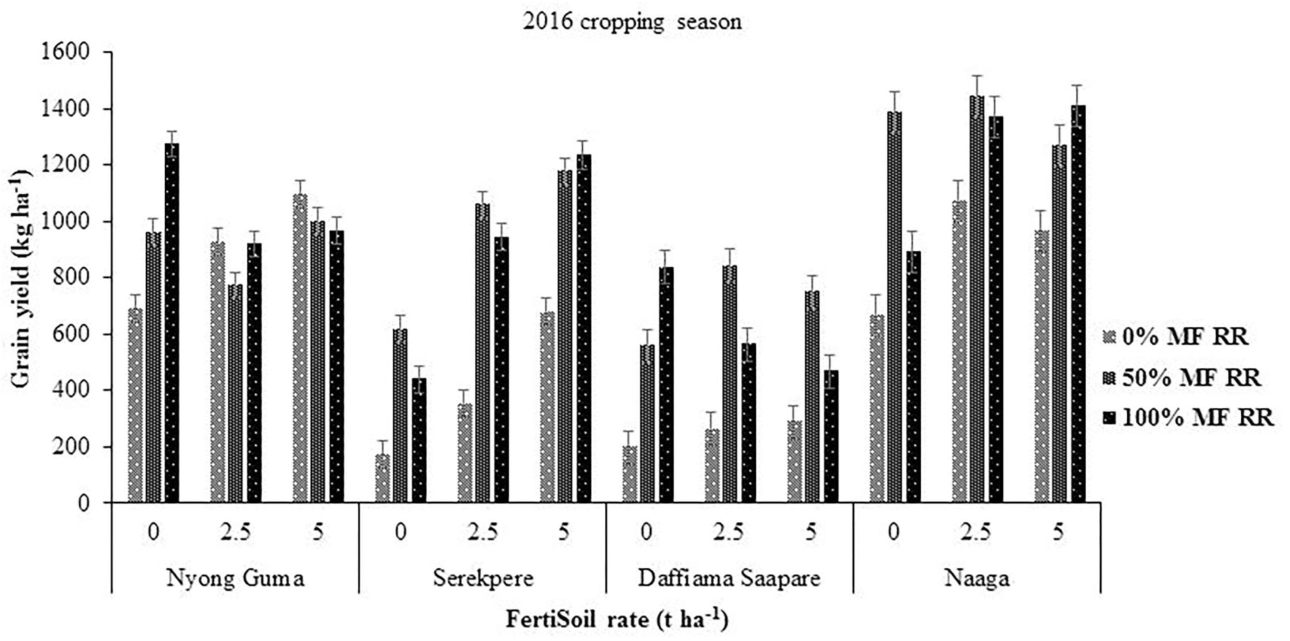

FIGURE 1 | Soybean yield response to mineral fertilizer, FertiSoil or in combinations for 2016 cropping season at the study locations. Error bars represent standard error of difference (SED).

5 t ha^{-1} resulted in a significant increase in grain yield from 1,194 kg ha^{-1} in the control to over 2,000 kg ha^{-1} except for the 100% RR mineral fertilizer + 2.5 t ha^{-1} FertiSoil at Nyong Guma. The combined application of 100% RR mineral fertilizer and 2.5 or 5 t ha^{-1} FertiSoil increased the grain yield by 1,148 and 1,364 kg ha^{-1}, respectively, over that of the control at Serekpere (**Figure 2**). At Daffiama Saapare, the highest grain yield of 1,533 kg ha^{-1} resulted from the combined 5 t ha^{-1} FertiSoil and 50% RR mineral fertilizer treated plots (**Figure 2**). Application of FertiSoil, mineral fertilizer or in combination at different rates gave grain yields of above 2,000 kg ha^{-1} except FertiSoil at 2.5 t ha^{-1} at Naaga (**Figure 2**). However, the highest (2,768 kg ha^{-1}) grain yield resulted from the combined application of FertiSoil and mineral fertilizer at full rates.

Phosphorus Use Efficiency

The application of selected nutrient management options had significant ($p \leq 0.05$) effect on PUE across locations (**Table 5**). The application of 50% RR mineral fertilizer alone increased P use efficiency by 17% over the 100% RR mineral fertilizer at Nyong Guma. Similarly, the highest P use efficiency of 53% was recorded for the application of sole mineral fertilizer at half rate although it was not significantly ($p < 0.001$) different from the full rate at Serekpere. The PUE was highest (≈60%) in the 50% RR mineral fertilizer application and resulted in a

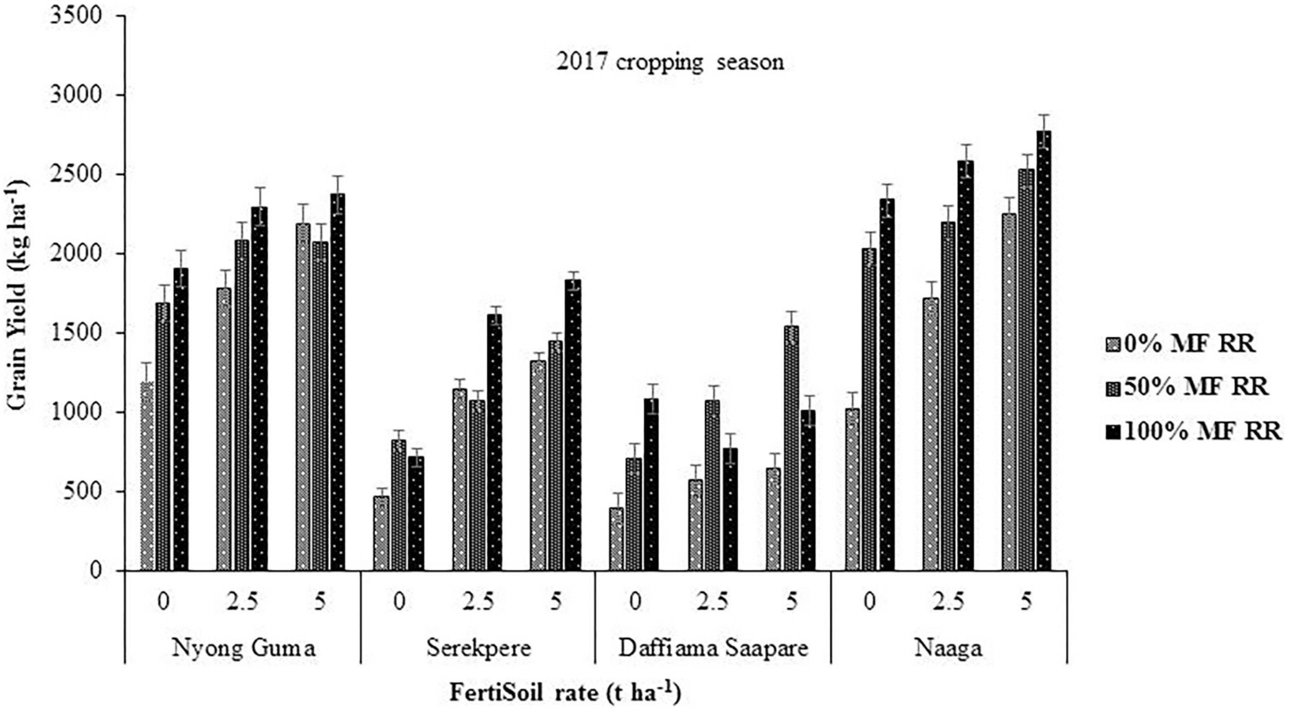

FIGURE 2 | Soybean yield response to mineral fertilizer, FertiSoil or in combinations for 2017 cropping season at the study locations. Error bars represent SED.

relative increase of over 100% compared to the other nutrient combinations applied at Daffiama Saapare. The sole application 50% RR mineral fertilizer had the highest (≈37%) PUE followed by the combined application of mineral fertilizer and FertiSoil at half rates (24%) which were both significantly ($p < 0.001$) different from the 100% RR mineral fertilizer and its integration with FertiSoil at different rates at Naaga. With the integrated application, 2.5 t ha^{-1} FertiSoil and 100% RR mineral fertilizer recorded the second highest PUE at Nyong Guma (14.54%). At Daffiama Saapare and Naaga, the combined application of 2.5 t ha^{-1} FertiSoil and 50% RR mineral fertilizer had higher PUE of 25.47 and 29.44%, respectively.

Influence of Nutrient Management Options on Soil Quality Indices

The soil physico–chemical and biological properties were significantly ($p \leq 0.05$) influenced by the nutrient management options across the locations (**Table 6**). At Nyong Guma, 6 out of the 12 indicators tested showed significant differences between the treatments. Exchangeable K and Mg were significantly ($p > 0.001$) higher under combined application of 100% RR mineral fertilizer and 5 t ha^{-1} FertiSoil with values of 0.71 and 0.65 $\text{cmol}_{(+)}$ kg^{-1}, respectively, compared to 0.22 and 0.24 $\text{cmol}_{(+)}$ kg^{-1}, respectively, in the control. The microbial C and P increased by 38.1 and 43 mg kg^{-1}, respectively, with the co-application of 100% RR mineral fertilizer and 5 t ha^{-1} FertiSoil and 50% RR mineral fertilizer and 5 t ha^{-1} FertiSoil, respectively, in relation to the control.

A relative increase of over 50% in aggregate stability was observed under FertiSoil application alone or in combination with mineral fertilizer except the 50% RR mineral fertilizer + 5 t ha^{-1} FertiSoil which was 39% at Serekpere. Additionally, the combined application of 100% RR mineral fertilizer and 5 t ha^{-1} increased exchangeable Ca and Mg, microbial C and P by 2.84 and 0.56, $\text{cmol}_{(+)}$ kg^{-1} 102.7 and 33.37 mg kg^{-1}, respectively, compared to the control.

At Daffiama Saapare, the integration of mineral fertilizer and FertiSoil at 100% RR had the highest (0.12%) total N content which was significant ($p > 0.001$) different from the control. The combined application of mineral fertilizer and FertiSoil at 50 or 100% RR equally increased exchangeable K by 44% comparative to the control. Also, the co-application of 100% RR mineral fertilizer and 5 t ha^{-1} resulted in an increase in exchangeable Mg (250%), microbial N (470%) and P (183%) levels in relation to the control.

Seven out of 12 indicators were found to be significantly ($p \leq 0.05$) affected by the nutrient management options at Naaga. The sole application of 5 t ha^{-1} FertiSoil increased pH from 5.18 in the control to 5.92. Applying 100% RR mineral fertilizer to 2.5 t ha^{-1} FertiSoil increased organic C (42%) and available P (12%) contents. The highest [5.84 $\text{cmol}_{(+)}$ kg^{-1}] exchangeable Ca value was recorded in the 100% RR mineral fertilizer + 5 t ha^{-1} treated plot and was significantly ($p < 0.001$) from the control.

The SQI values showed significant ($p < 0.001$) variations among different nutrient inputs (**Figure 3**). The combined

TABLE 5 | The PUE of mineral fertilizer and FertiSoil by soybean on non-responsive soils.

Nutrient input	PUE (%)			
	Nyong Guma	Serekpere	Daffiama Saapare	Naaga
0%MF+50%FS	2.56^{e}	11.32^{c}	8.89^{d}	5.43^{e}
0%MF+100%FS	11.66^{cd}	12.15^{c}	4.17^{e}	7.60^{de}
50%MF+0%FS	16.13^{a}	53.03^{a}	59.48^{a}	36.70^{a}
50%MF+50%FS	12.87^{bc}	17.02^{bc}	25.47^{b}	29.44^{b}
50%MF+100%FS	11.10^{cd}	11.84^{c}	24.91^{b}	9.38^{d}
100%MF+0%FS	13.80^{abc}	51.01^{a}	22.15^{b}	12.85^{c}
100%MF+50%FS	14.54^{ab}	21.49^{b}	14.90^{c}	12.59^{c}
100%MF+100%FS	9.79^{d}	16.22^{bc}	9.73^{d}	9.20^{d}
Fpr	<0.001	<0.001	<0.001	<0.001
CV (%)	12.5	15.9	11.3	10.9

Different letters within the same column show significant differences at $p \leq 0.05$ (Tukey HSD).

application of mineral fertilizer and FertiSoil at 100% RR had the highest (0.82) SQI, followed by 100% RR mineral fertilizer + 2.5 t ha^{-1} (SQI = 0.70).

Economic Assessment

The economic viability of the selected nutrient management options for the two cropping seasons is presented in **Table 7**. In the 2016 cropping season, the VCR for the sole application of mineral fertilizer at 50% RR ranged from 2 to 5.2 across the study sites. However, the 100% RR mineral fertilizer application was the most profitable in Nyong Guma (3.0) and Daffiama Saapare (4.1). The sole application of FertiSoil or in combination with mineral fertilizers at different rate had VCR values below 2 in all the study locations.

In the second year, incorporation of mineral fertilizers at 50% RR had a VCR above the economic threshold of 2 (2.8–7.6) in all the study locations. The VCR of the 100% RR mineral fertilizer application also had the range from 3.8 to 6.9 in all the study locations except for Serekpere (VCR =1.7). On the contrary, the sole addition of FertiSoil at 2.5 and 5 t ha^{-1} at all the study locations had a VCR below 1. The combined application of 50% RR mineral fertilizer with 2.5 or 5 t ha^{-1} FertiSoil recorded VCR values <2 in all the study locations with the exception of Daffiama Saapare (VCR = 5.9 and 5.6, respectively). Similarly, the co-application of 100% mineral fertilizer with 2.5 or 5 t ha^{-1} FertiSoil gave VCR values of <2 across locations excluding Daffiama Saapare (VCR = 6.1 and 5.4, respectively).

DISCUSSION

Mineral Fertilizer and Compost on Soybean Grain Yield and P Use Efficiency

Generally, the combined application of FertiSoil and mineral fertilizer at different rates significantly increased grain in all the locations across seasons. Such positive yield responses following site specific integrated nutrient management have been reported by other authors (Kumaragamage, 2010; Adeyinka, 2016; Rurinda et al., 2020). The crop yield increases under compost and mineral fertilizer application have been expressed as improved synergy and/or additive effect, soil fertility improvement and priming of soil properties (Kuzyakov et al., 2000; Vanlauwe et al., 2001). The synergistic interaction observed in this study could be ascribed to Liebig–synergism, where the increased yield were obtained following the application of the most limiting nutrients and resolving deficiencies (Wallace, 1990; Rietra et al., 2017). It could be inferred that the supply of Ca, Mg, S, Zn, and B was critical for achieving the maximum P utilization and yield. Calcium may have increased the levels of plant hormones, indoleacetic acid, and gibberellin, which boost soybean growth and yield (Ha et al., 2022). Magnesium is required for a number of biological processes in leaves, including CO_2 fixation in photosynthesis, photophosphorylation, protein and chlorophyll production, phloem loading, and assimilate translocation (Wang et al., 2020).

To boost the crop yield, photosynthetic assimilates from leaves are transferred to sink organs (such as seeds) increasing higher number of grains per plant (Rodrigues et al., 2021). Sulfur plays a key role in nitrogenase biosynthesis and activity, enhance nodule metabolism, N_2 fixation, plant growth, photosynthesis, and seed yield in legumes (Becana et al., 2018). Zinc is an essential component of several enzymes that mediate a variety of metabolic reactions in plants, as well as carbohydrate, protein, and chlorophyll formation (Mallarino et al., 2017). Boron plays a significant role in the plant metabolism by influencing the enzyme activity, cell division, carbohydrate transport, calcium and potassium uptake, and protein synthesis, nodulation and fixation of atmospheric N, all of which contribute to pod and seed production (Pawlowski et al., 2019).

Bharali et al. (2017) reported an enhanced photosynthesis process and efficient assimilation due to organic and inorganic fertilizer amendments contributing to higher rate of grain yield.

The application of the compost stimulates microbial growth and activity and releases nutrients for plant uptake and overall high crop yields (Tejada et al., 2009; Larney and Angers, 2012). Further, the compost improves the soil organic C stock and fertility for better yields (Scotti et al., 2015). Vanlauwe et al. (2011) attributed increase in grain yield due to the combined compost and mineral fertilizer to improved agronomic use efficiency of

TABLE 6 | Physico–chemical and biological properties as affected by mineral fertilizer and FertiSoil.

Soil Quality Indicator*	Nutrient input*	0MF 0FS	0MF 50FS	0MF 100FS	50MF 0FS	50MF 50FS	50MF 100FS	100MF 0FS	100MF 50FS	100MF 100FS	CV (%)
Nyong Guma											
P		5.7^{cd}	5.6^{d}	5.9^{abc}	6.0^{ab}	6.0^{ab}	5.8^{bcd}	5.7^{cd}	5.9^{abc}	6.1^{a}	1.7
K		0.22^{d}	0.40^{bc}	0.41^{bc}	0.43^{b}	0.38^{bc}	0.37^{bc}	0.30^{cd}	0.41^{bc}	0.71^{a}	9.4
Mg		0.24^{c}	0.45^{bc}	0.52^{bc}	0.64^{b}	0.46^{bc}	1.10^{a}	0.46^{bc}	0.54^{bc}	0.65^{b}	19.8
BD		1.66^{cd}	1.76^{b}	1.83^{ab}	1.86^{a}	1.81^{ab}	1.84^{ab}	1.80^{ab}	1.65^{d}	1.75^{bc}	1.9
C_{mic}		199.5^{c}	212.5^{bc}	212.4^{bc}	199.3^{c}	214.4^{bc}	218.0^{abc}	213.4^{bc}	237.6^{a}	228.4^{ab}	3.2
P_{mic}		24.9^{b}	38.2^{b}	42.8^{ab}	40.5^{b}	38.6^{b}	67.9^{a}	40.1^{b}	43.4^{ab}	48.3^{ab}	21.0
Serekpere											
K		0.29^{d}	0.39^{cd}	0.47^{bc}	0.56^{ab}	0.56^{ab}	0.48^{bc}	0.53^{ab}	0.51^{abc}	0.62^{a}	9.7
Ca		2.61^{c}	4.20^{abc}	4.77^{ab}	3.35^{bc}	4.61^{ab}	4.54^{ab}	3.54^{bc}	4.47^{abc}	5.45^{a}	15.7
Mg		0.26^{d}	0.54^{b}	0.51^{b}	0.36^{cd}	0.61^{b}	0.52^{b}	0.47^{bc}	0.57^{b}	0.82^{a}	9.0
AS		43.35^{d}	69.17^{a}	65.32^{abc}	65.06^{abc}	67.89^{a}	60.3^{c}	61.58^{bc}	68.30^{a}	66.82^{ab}	3.0
C_{mic}		282.0^{b}	276.1^{b}	278.4^{b}	318.5^{ab}	346.9^{ab}	363.8^{a}	360.0^{a}	349.9^{ab}	384.7^{a}	12.2
P_{mic}		20.84^{c}	38.54^{b}	39.14^{b}	35.79^{b}	46.28^{ab}	42.82^{ab}	40.63^{b}	43.17^{ab}	54.21^{a}	15.4
Daffiama Saapare											
pH		5.70^{ab}	5.70^{ab}	5.99^{a}	5.90^{ab}	5.67^{ab}	5.69^{ab}	5.56^{b}	5.78^{ab}	5.62^{ab}	2.5
TN		0.07^{d}	0.11^{ab}	0.09^{bcd}	0.09^{bcd}	0.08^{bcd}	0.12^{a}	0.09^{bcd}	0.11^{ab}	0.10^{abc}	9.6
K		0.29^{e}	0.38^{cd}	0.34^{d}	0.35^{cd}	0.52^{ab}	0.55^{a}	0.49^{b}	0.40^{c}	0.52^{ab}	4.3
Mg		0.22^{c}	0.39^{bc}	0.46^{bc}	0.49^{b}	0.47^{bc}	0.47^{bc}	0.51^{ab}	0.63^{ab}	0.77^{a}	18.9
C_{mic}		230.3^{cd}	301.2^{b}	310.9^{b}	202.1^{d}	262.9^{bc}	302.4^{b}	312.1^{b}	500.1^{a}	284.7^{bc}	11.1
N_{mic}		63.4^{f}	91.7^{ef}	259.4^{b}	268.3^{b}	162.2^{cde}	226.1^{bc}	216.8^{bcd}	148.1^{de}	361.6^{a}	12.2
P_{mic}		19.0^{c}	34.3^{b}	37.1^{b}	35.6^{b}	37.7^{b}	37.7^{b}	39.3^{b}	44.3^{ab}	53.7^{a}	10.6
Naaga											
pH		5.18^{c}	5.69^{a}	5.92^{a}	5.89^{a}	5.60^{abc}	5.20^{bc}	5.66^{ab}	5.50^{abc}	5.49^{abc}	2.9
OC		0.41^{c}	0.55^{a}	0.51^{ab}	0.47^{bc}	0.52^{ab}	0.47^{bc}	0.56^{a}	0.58^{a}	0.52^{ab}	7.5
P		5.82^{b}	5.82^{b}	5.61^{b}	6.03^{ab}	5.93^{ab}	6.13^{ab}	5.90^{ab}	6.49^{a}	5.82^{b}	3.6
K		0.23^{f}	0.35^{e}	0.48^{cd}	0.41^{de}	0.54^{bc}	0.75^{a}	0.63^{b}	0.52^{c}	0.57^{bc}	10.8
Ca		2.87^{e}	3.94^{cd}	5.11^{ab}	3.64^{de}	4.78^{bc}	5.18^{ab}	4.75^{bc}	4.99^{ab}	5.84^{a}	11.8
Mg		0.28^{f}	0.61^{e}	0.59^{e}	0.53^{e}	0.96^{d}	0.58^{e}	1.47^{b}	1.35^{c}	1.81^{a}	4.0
P_{mic}		24.22^{f}	40.92^{e}	38.75^{e}	41.89^{e}	60.29^{d}	42.21^{e}	68.12^{c}	76.76^{b}	83.91^{a}	3.1

**MF: Mineral fertilizer rates: 30 P, 20 K, 10 Mg, 15 S, 15 Ca, 2.5 Zn, 0.5 B (kg ha^{-1}): FS: FertiSoil rate 5 t ha^{-1}. Applications at 50 and 100% recommended rate (RR). Dystric Plinthosol (Nyong Guma), Gleyic Lixisol (Serekpere), Ferric Lixisol (Daffiama Saapare), Dystric Leptosol (Naaga). pH: soil acidity, OC: organic carbon (%), TN: total nitrogen (%), P: available phosphorus (mg kg^{-1}), K: exchangeable potassium [cmol$_{(+)}$ kg^{-1}], Ca: exchangeable calcium [cmol$_{(+)}$ kg^{-1}], Mg: exchangeable magnesium [cmol$_{(+)}$ kg^{-1}], AS: aggregate stability (%), BD: bulk density (g cm^{-3}), C_{mic}: microbial carbon (mg kg^{-1}), N_{mic}: microbial nitrogen (mg kg^{-1}), P_{mic}: microbial phosphorus (mg kg^{-1}). Different letters within the same column show significant differences at $p \leq 0.05$ (Tukey HSD).*

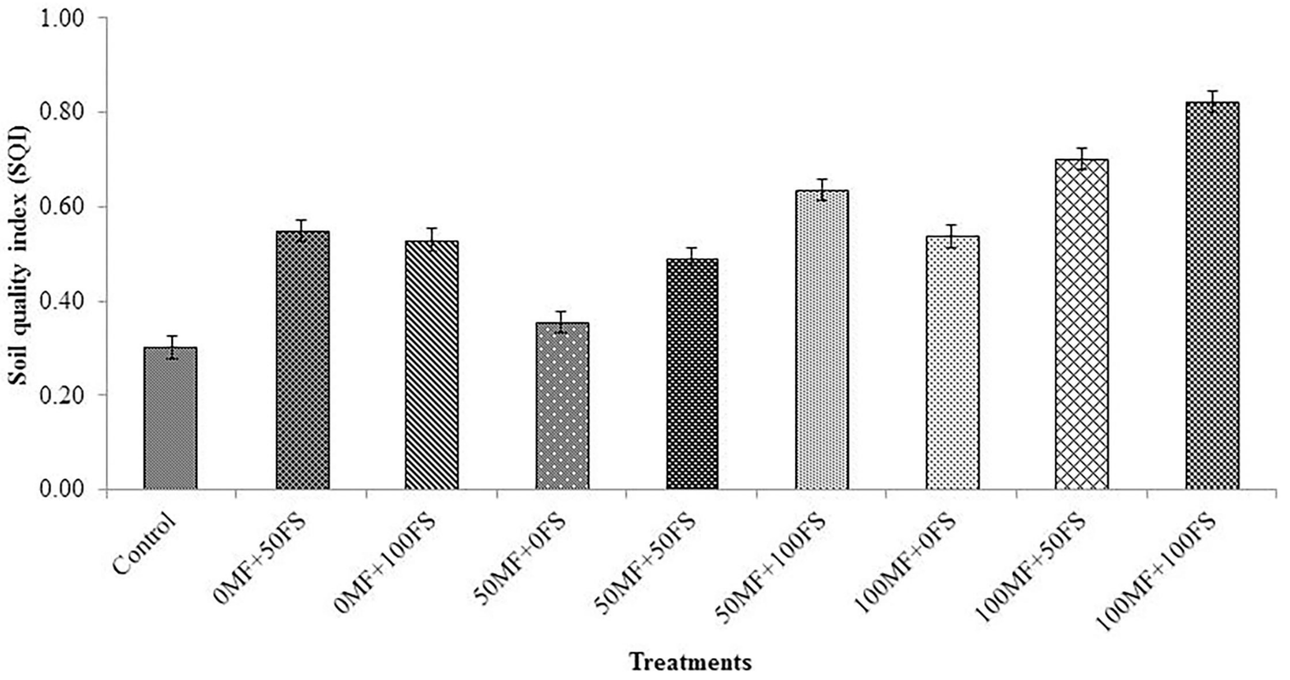

FIGURE 3 | The SQI values under different nutrient management options. Error bars represent standard error of difference (SED).

TABLE 7 | The VCR of mineral fertilizer and FertiSoil application in study locations.

	VCR							
	2016				2017			
Nutrient input	**Nyong Guma**	**Serekpere**	**Daffiama Saapare**	**Naaga**	**Nyong Guma**	**Serekpere**	**Daffiama Saapare**	**Naaga**
0%MF+50%FS	0.4	0.3	0.1	0.6	0.8	0.9	0.9	0.2
0%MF+100%FS	0.3	0.4	0.1	0.2	0.7	0.6	0.9	0.2
50%MF+0%FS	2.0	3.8	3.1	5.2	3.7	3.2	7.6	2.8
50%MF+50%FS	0.1	1.3	0.9	1.1	1.1	0.8	5.9	0.9
50%MF+100%FS	0.2	0.8	0.4	0.5	0.6	0.7	5.6	0.8
100%MF+0%FS	3.0	1.7	4.1	1.1	3.8	1.7	6.9	4.6
100%MF+50%FS	0.3	1.1	0.5	0.9	1.3	1.4	6.1	0.5
100%MF+100%FS	0.2	0.8	0.2	0.5	0.8	0.9	5.4	0.4

mineral fertilizers. The high quality of compost (N > 2.5%, polyphenol 5.95%, and lignin 0.69%) applied in this study could have accounted for the increased yield by readily releasing nutrients to meet crop demand (Palm et al., 2001; Ulzen et al., 2019).

The application of the mineral fertilizer or in combination with FertiSoil at different rates significantly increased P use efficiency. However, the highest P use efficiency was observed with the application of 50% RR mineral fertilizer across the locations. The results obtained are in accordance with the findings of a study by Kihara et al. (2017) who observed the highest nutrient use efficiency under low mineral fertilizer application rates. This is, however, inconsistent with the findings of Koocheki and Seyyedi (2015) who observed the high P use efficiency with the increasing fertilizer rates.

Girma et al. (2017) reported high PUE under combined application of organic and inorganic fertilizers at half rates, which is in line with this study. Golla (2020) stated that the high nutrient use efficiency is attained under the integrated nutrient managements as the nutrients' losses are minimized.

Soil Quality Indicators

The soil quality assessment based on minimum dataset (MDS) to evaluate soil quality in different soil managements have been used widely (Li et al., 2019; Jiang et al., 2020). In this study, the MDS used were pH; organic C; total N; available P; exchangeable cations (K, Ca, Mg); microbial C, N, and P; bulk density and aggregate stability using a one-way ANOVA.

The integrated nutrient applications had greater significant positive influence on the soil quality variables across locations (**Table 5**). The application of mineral fertilizer and compost provided a well-balanced and higher quantities of nutrients which further improved their soil nutrient content (Bhattacharyya et al., 2006). Compost has stable nutrient pools that release nutrients slowly and sustain microbial biomass and improve microbial activity involved in nutrient cycling (Murphy et al., 2007; Poblete-Grant et al., 2019). The improved aggregate stability with the co-application of compost and mineral fertilizer corroborates the results of Yüksek et al. (2009) and Guo et al. (2019). The observed stabled aggregates were due to organic matter increases through organic amendments which acts as cementing factor that flocculates soil particles to form stable aggregates (Tejada et al., 2006). The stable aggregates and soil structure are achieved through inter-particle cohesion within aggregates and by improving their hydrophobicity thereby reducing their breakdown (Diacono and Montemurro, 2011). The rise in soil pH is attributed to the alkalinity production of the compost through H^+ and organic anions reactions in soil exchange site and the ammonification of organic N (Xu et al., 2006; Butterly et al., 2013). The readily available C and N in the compost could explain the increased microbial biomass, which increased root biomass and exudates microbial utilization, growth, and stabilization of enzymes to humic substances (Trasar-Cepeda et al., 2008).

Higher SQI under integrated nutrient managements have also been reported (Sharma et al., 2018; Roy et al., 2022). Mukherjee and Lal (2014) reported that the closer the SQI is to 1, the better the quality of the soil and the potential of that management option to improve the soil.

Economic Appraisal

The economic profitability of nutrient management practices was higher in 2017 compared to the 2016 cropping season. This was due to the maximum grain yields obtained in 2017 cropping season and their associated high gross income. The sole application of mineral fertilizers at different rates in both years were highly profitable (average VCR = 11). Findings in this study are consistent with Dicko et al. 2017 and Sitienei et al. (2018) confirming the high profit potential of applying mineral fertilizers on crops. The implication of these results reiterates the integral role of site-specific nutrients application in sustainable crop production, soil fertility management (Angus et al., 2004; Ogundijo et al., 2015), and overall maximizing the net financial returns of farmers. This is in contrast to results of previous studies that reported unprofitable returns with mineral fertilizer application (Nkonya et al., 2005; Diallo et al., 2016). According to Lécuyer et al. 2014, high fertilizer rate application and its accompanying high prices, low agronomic use efficiency as well as low market price of output affect economic profitability and could have contributed to this contrasting result. The application of FertiSoil at 2.5 and 5 t ha^{-1} were not economically viable as VCR for all the sites were below 1 in both cropping seasons. A VCR of 2 and above is commonly used as the economic threshold for profitability attractive to farmers (Morris et al., 2007). Conversely, Tovihoudji et al. (2018) reported VCR values >2 and above 4 were obtained for the application for compost at 3 and 6 t ha^{-1}, respectively. The difference in VCR value is attributed to their lower cost of compost (USD4 for a ton) compared to USD96 per ton used in this study. The profitability depends on a lower ratio and as input price increases the VCR decreases. The profitability of a nutrient management option is dependent on input cost, crop response to input, and market grain output prices (Richards et al., 2015). Farmers can, however, substitute commercial compost with crop residues, household wastes, and animal manure of high quality.

CONCLUSIONS

The site-specific integrated nutrient management is a potential approach to obtain positive soybean grain yields, nutrient use efficiency, soil fertility, and economic benefits in non-responsive soils. Smallholder farmers can obtain over 2,000 kg ha^{-1} in soybean production when soil nutrient managements are tailored to site-specific macro and micronutrient requirements alongside the organic amendments. The efficient use of P fertilizer is enhanced when secondary, micronutrient and organic amendments are applied. The co-application of organic amendments and site-specific fertilizer application is the best soil nutrient management for crop response on non-responsive soils. The primary of role soil organic matter in improving soil quality for sustainable crop production has been highlighted. Evaluation of site-specific limiting nutrients in different agro–ecological zones and incorporation of same into fertilizer recommendation programs is paramount.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

RA, RCA, AO, and SA-N: research conceptualization. RA, RCA, and AO: set up the experiment. RA: collection, analyses and interpretation of data, and manuscript write up. RCA, AO, and SA-N: manuscript review and editing. All authors made a significant contribution to manuscripts. All authors contributed to the article and approved the submitted version.

FUNDING

The authors would like to acknowledge the Bill and Melinda Gates Foundation's financial contribution to this work through a grant (OPP1020032) to Wageningen University' and Research's Plant Production Systems Group on the project N2Africa-Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa.

ACKNOWLEDGMENTS

The authors are grateful to the Kwame Nkrumah University of Science and Technology for infrastructural and technical support.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.