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RESEARCH ARTICLE

SOIL TILLAGE VARIANTS AND SULPHUR FERTILIZATION AFFECT NODULATION, N2 FIXATION AND YIELD OF BAMBARA GROUNDNUT *(Vigna subterreana)* IN SOUTHEAST NIGERIA

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ABSTRACT

Management efficiency can increase crop productivity through enhanced N2 fixation in the plant-soil system. This study examined soil tillage variants and sulphur fertilization effects on nodulation, N2 fixation effectiveness and yield of Bambara groundnut [*Vigna subterranea*] in a degraded Ultisol in Agbani Enugu, Southeast Nigeria. Twenty-four experimental units were laid out in a Randomized Complete Block Design (RCBD). The six treatments comprised No-Till+No Gypsum (NTGo), No-Till+Gypsum$_1$ (NTG_1), No-Till+Gypsum$_2$ (NTG_2), Till+No Gypsum (TGo), Till+Gypsum$_1$ (TG_1), and Till+Gypsum$_2$ (TG_2). No-till+gypsum2 plots had significantly higher soil N content than each corresponding No-till+no gypsum plot by 15-40 %. At 30 DAP, the plots treated with till+gypsum1 (21 kg/ha), till+gypsum2 (42 kg/ha), no-till+gypsum2 (42 kg/ha), no-till+gypsum1 (21 kg/ha), and till+no gypsum had 62-63 % higher soil sulphur content (P= 0.05) than the control plots. The nodule count per plant in plots treated with no-till+gypsum2 (42 kg/ha) was greater than that in the control plot, plots with no-till+gypsum1 (21 kg/ha), and plots with till+gypsum2 (42 kg/ha) by 72-74 % at 30, 60, and 90 DAP across two seasons. Compared to the untreated plots, nodulation effectivity was raised by 79-89 % in the No-till+gypsum2 plot. The plots treated with no-till+gypsum2 (42 kg/ha) had the highest yield (0.94 t/ha), followed by plots treated with no-till+gypsum1 (42 kg/ha) with 0.93 t/ha dry seed yield and till+gypsum2 (42 kg/ha) with 54-55 % greater yield (P=0.05) than the control plot. Sulphur treatment boosted nodulation by 68 % and nodule effectiveness by about 78 %. The no-till+Gypsum2 application enhanced the average yield of Bambara groundnuts by 56 %. The soil application of S enhanced the amount of accessible S in the soil. Results show that the tillage system and S fertilization impact Bambara groundnut on degraded Ultisols. Dry matter yield was best with a high S supply in both S increments and no-till systems. The number and effectiveness of nodules increased at different S rates and no-tillage. Because of the increased S application rate, there was a considerable increase in N accumulation due to a greater N2 fixation rate. The study recommends using no-till systems and sulphur fertilization practices to enhance crop productivity, especially in degraded Ultisols. The study provides valuable insights into sustainable agriculture practices that boost yields while conserving soils.

KEYWORDS

Soil Tillage variants, Sulphur fertilization, N-fixation, Bambara groundnuts, Tropical Ultisol

1. BACKGROUND

The Bambara groundnut (*Vigna subterranea*), which was developed in West Africa, has long been cultivated throughout tropical Africa. The crop is accessible annually as an inexpensive protein, energy, and food source. It is appropriate for the African agricultural system in use today and significantly contributes to food security. It has a reputation for fixing atmospheric nitrogen (N2), which improves soil fertility and lessens the demand for artificial fertilizers. However, different agronomic techniques, including soil tillage and sulphur fertilization, might affect the performance of Bambara groundnut (Majola et al., 2021; Soumare et al. 2022).

This annual legume comes in a variety of forms, including Open (Spreading), Compact (bunched), and Intermediate (semi-bunch). Usually with a white hilum that may be bordered by a black or brown eye, the pod contains one or sometimes two firm spherical seeds that are 7 to 15 mm in diameter and come in a variety of colours (white, black, red, and often speckled and patterned) (Winch, 2006). Although yields of less than 100 kg/ha are not unusual, the average yield is 300–800 kg/ha (Brink et al., 2006). According to Baudoin and Mergeai, conventional farming yields of dry seeds typically fall between 300 and 800 kg/ha and may approach 3,000 kg in intensive farming (Baudoin and Mergeai, 2001). Some researchers reported hectare-level yields of 500–1000 kg dry nuts (Williams et al., 1979).

The plant contains several geotropic lateral roots and a well-developed taproot. The right Rhizobia are linked to the nitrogen root to form a nodule. Because they can 'fix' atmospheric nitrogen symbiotically into the soil, legumes are essential for the environment, agriculture, and economy in many cropping systems. Environmental contamination is considerably

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exacerbated by nitrogen fertilizer (Savci, 2012; Olivera et al., 2004). The relationship between legume growth, nitrogen fixation, phosphorus, and potassium availability is well-established (Weisany et al., 2013). Understanding the impacts of various soil tillage techniques and sulphur fertilizer on the nodulation, N2 fixation, and production of legume crops has attracted increasing attention in recent years. According to research, soil tillage techniques, including traditional ploughing, reduced tillage, and no-till affect soil structure, nutrient availability, and microbial activity, which in turn affects plant growth and development (Stenberg et al., 2020; Blanco-Canqui et al., 2019).

Sulphur is becoming recognized as the fourth major plant nutrient after nitrogen, phosphorus, and potassium. In addition, sulphur (S) is a critical macronutrient for plant development and is needed for legume nodulation, nitrogen metabolism, and N2 fixation (White and Veneklaas, 2012). However, leaching and mineralization processes may restrict the amount of S in soil, particularly in tropical areas. To improve legume performance and N2 fixation, sulphur fertilization approaches have drawn more attention (Das and Ghosh, 2018; Gao et al., 2015).

Sulphur has a significant role in crop productivity and is becoming increasingly essential in agriculture (Scherer, 2008). For one tonne of seed, legumes need around eight kg of sulphur (range 5–13). As the amount of sulphate in the soil has not been considered a limiting factor for plant development, the impact of sulphur supply on nitrogen fixation has received less attention. The structural and enzymatic elements of plants both need sulphur. Sulphur is necessary for synthesizing proteins and is a vital component of several critical amino acids. Sulphur is also required to synthesize chlorophyll, which causes crops to develop quickly and reach maturity early (Schmidt and Jäger, 1992). However, due to declining anthropogenic sulphur input and a lack of input via sulphur fertilization to make up for exporters, agricultural sulphur deficits have been documented often during the last ten years (Scherer, 2008). The significant reactions to sulphur fertilization at high nitrogen fertilization levels highlighted the requirement for precise sulphur application in intensive crop production systems. Continued nitrogen fertilization on low- sulphur soils without additional sulphur will lower the flour quality (De Ruiter and Martin, 2001; Flaete et al., 2005).

There are several places to get sulphur for fertilizer. Organic matter is the primary source of soil sulphur and organic sulphur compounds. Rainfall and sulphate-containing fertilizers are other sources of sulphur. Ammonium sulphate, potassium sulphate, gypsum, and zinc sulphate are readily accessible supplies (Oldham, 20110. Other sulphate sources abound, but sources of sulphur in its elemental or sulphide form are less common. Gypsum is the least expensive and most accessible option for addressing the sulphur shortage and enhancing the physicochemical qualities of the soil. However, the host plant's four main nitrogen-accumulation capacities, the amount of nitrogen in the soil, and environmental restrictions all play a significant role in the biological nitrogen fixation (BNF) process (Van Kessel and Hartley, 2000). The soil enormously impacts nitrogen fixation, plant growth, and ultimate yield as a plant development medium. Acidity, salinity, alkalinity, temperature, wetness, fertility, and structure are a few variables that affect the soil environment (Hungria and Vargas, 2000). As a result, the environment must be managed.

Tillage is one of the best strategies for the soil environment, which impacts nitrogen fixation (Kihara et al., 2012). Minimum tillage, reduced tillage, no-tillage, conventional tillage, and other variations of conservation tillage exist. The environment and soil system must also be taken into account. Soil tillage is an essential agricultural practice influencing soil's physical characteristics and crop output (Keshavarzpour and Rashidi, 2008). Since management effectiveness may promote agricultural productivity via better N2 fixation in the plant-soil system, it is hypothesized that modification of soil tillage and sulphur (S) fertilization approach would affect nitrogen fixation and yield of legume crops. However, only a tiny amount of study has been done to determine the combined impacts of different soil tillage techniques and sulphur fertilizer on the nodulation, N2 fixation, and yield of Bambara groundnut, especially in the setting of southeast Nigeria. To maximize crop output and ensure sustainable agricultural practices in the area, it is essential to understand how different agronomic techniques interact.

The study's main objective is to examine soil tillage variants' and sulphur fertilization effects on nodulation, N2 fixation effectiveness, and yield of Bambara groundnut [*Vigna subterranean (L*) verde] in a degraded Ultisol in Agbani, southeast Nigeria.

2. Materials and Methods

2.1 Description of the experimental site

The experiment was conducted for two consecutive planting seasons (2021 and 2022) at the Faculty Research Farm of Agriculture and Natural Resources Management, Enugu State University of Science and Technology, Nigeria (06° 52'N, 07° 15'E; mean elevation 450 m above sea level). The yearly rainfall in the area ranges from 1700 to 2010 mm. The rainfall pattern is bimodal between April and October, with the dry season falling between November and March. The soils' textural class is loam with an-iso-hyperthermic soil temperature regime and is classified as Typic Paleustult (Ezeaku and Anikwe, 2006; Anikwe and Obi, 1999).

2.2 Field method and design

The field was traditionally cleared with cutlass, and hoes mapped out with measuring tape, rope, and pegs to obtain a total area of 307.5m² (15 m x 20.5 m) for the experiment. The field was divided into four blocks, and each was further divided into six experimental units. The subplot area is 9 m² (3m x 3m), the space between the block is 1m apart, while plots are separated by 0.5m alley. Twenty-four experimental units were laid out in a Randomized Complete Block Design (RCBD). The six treatments comprised No-Till+No Gypsum (NTGo), No-Till+Gypsum$_1$ (NTG$_1$), No-Till+Gypsum$_2$ (NTG$_2$), Till+No Gypsum (TG$_o$), Till+Gypsum$_1$ (TG$_1$), and Till+Gypsum$_2$ (TG$_2$). Gypsum$_1$ (G$_1$) represents 21 kg/ha or 0.021 tons/ha, with an anhydrite sulphur of 4.94. Gypsum$_2$ (G$_2$) represents 42 kg/ha or 0.042 tons/ ha, with an anhydrite sulphur of 9.87.

The experimental units comprised two rates (21 Kg ha^{-1} and 42 Kg ha^{-1}) of gypsum and two tillage systems. Conventional tillage (tilled plots on raised beds were prepared manually with traditional hoes) and No-Tillage plots were on flatbeds. The Bambara groundnut seed and NPK 15:15:15 were obtained from the Enugu State Agricultural Development of Agricultural Programme (ENADEP), and gypsum was obtained from Nigerian Cement Company Nkalagu Ebonyi State, Nigeria. Gypsum was applied two weeks before planting by evenly spreading the pulverized powder on the respective plots and mixing it with the topsoil. The crop was planted at a spacing of 45 x 15cm at the rate of two seeds per hole, totalling 1481 plants/ha. Seeds that did not germinate one week after planting were supplied; some were thinned down to one plant per hole two weeks after planting. There was a basal application of NPK 15:15:15 fertilizer at 120 Kg ha^{-1} two weeks after planting. One weeding regime was carried out manually using a traditional small hoe at 21 DAP. Subsequently, rouging was employed to reduce weed competition in each season.

2.3 Observation and Data Collection

Total nitrogen (N), potassium (K), calcium (Ca), available phosphorus (P), sodium (Na), magnesium (Mg), pH, SOC, and cation exchange capacity were measured in soil samples (taken from 5 locations in each plot at 0, 30, 60, 90, and 120 DAP) (CEC). The macro Kjeldahl method was used to determine total nitrogen (Bremner, 1982). Available P was determined using the Bray II method as outlined in Olsen and Sommers (Olsen and Sommers, 1982). Soil organic carbon (SOC) was analyzed by the Walkley/Black procedure (Nelson and Sommers 1996). The pH of the soil in KCl was determined using a glass electrode pH meter (McLean 1983). Rhoades' method was used to determine the exchangeable cations and cation exchange capacity (CEC) (Rhoades, 1983). The hydrometer technique was used to determine the particle size distribution (Gee and Orr 2002). Dry bulk density was determined by the core method (Grossman and Reinsch, 2002). Total porosity values were derived from bulk density data. Saturated hydraulic conductivity (Ksat) was determined by the method of Klute and Dirksen (Klute and Dirksen, 1986).

The Meter rule was used to measure plant height from the base level to the tip of the last formed leaf. Five plants were chosen randomly, measured in each plot, and then averaged to give plant height per plant. Five plants were randomly selected from each plot to determine the number of leaves. The number of leaves was averaged to determine the number of leaves per plant. Five plants per plot were also harvested to get the fresh pod yield at 120 DAP, and the fresh pods were weighed on a scale, and the average was taken to give the pod weight per plant. Also, the leaf area index was determined at 30, 60 and 90 DAP according to the method of Watson (Watson, 1958).

The number of nodules per plant was obtained at 30, 60, and 90 DAP, whereas the number of fresh pods was determined at harvest (90 DAP). In determining the number of nodules and fresh pods, a spade was used to scoop out the plant roots from the soil carefully. The soil with the roots was then immersed in a basin of water to remove the soil, the roots were recovered, and the nodules were counted manually. Nodulation effectivity was determined by randomly collecting five nodules and carefully slicing the nodules with a blade razor. The strong pink colour of the nodules is caused by the presence of leghemoglobin, which must be present for active nitrogen fixation. If a nodule is brown, white or green, it is considered ineffective. The number of fresh pods per plant at harvest was manually counted. Fresh pods per plant were weighed using an electronic weighing balance.

2.4 Data Analysis

The data from the experiment were analyzed using an analysis of variance test (ANOVA) based on Randomized Complete Block Design (RCBD) using *FLSD* at a 5% level of probability ($P<0.05$) according to techniques outlined by Steel and Torrie and detection between treatment means are described by (Steel and Torrie 1980; Obi, 2002).

3. Results and Discussion

3.1 Initial soil properties

The results of pre-planting soil analysis in both years are presented in Table 1. The results show that the textural class of the study site is loamy sand. The initial particle size in 2021 was viz. Clay (6%), Silt (9%), Sand (43%) and Coarse Sand (42%), whereas the value obtained in 2022 were Clay (7%), Silt (7%), Sand (41%) and Coarse Sand (45%), Soil dry bulk density was 1.69 for 2021 and 1.53 Mg m^{-3} for 2022, and the total porosity for the year 2021 and 2022 were respectively 36.23 g/cm^3 and 42.26 g/cm^3. The hydraulic conductivity of soil in 2021 and 2022 was 51.12 cm^3/hr and 27.88 cm^3/hr, respectively. The sulphur content of the soil was 0.0055 g/kg in 2021 and 1.588 g/kg in 2022. The soil pH in water was 5.6 and 5.2 in 2021 and 2022, respectively, The exchangeable cations content of the soil in 2021 were: Magnesium (Mg^{2+}) (1.00), Potassium (K^+) (0.18), Calcium (Ca^{+2}) (4.8), Sodium (Na^+) (0.10) and Cation exchange capacity (CEC) (7.20) cmol kg^{-1} whereas the values obtained in 2022 were Magnesium (Mg^{2+}) (1.20), Potassium (K^+) (0.19), Calcium Ca^{+2} (3.60, Sodium (Na^+) (0.11) and Cation exchange capacity (CEC) (7.20) cmol kg^{-1}. The percentage of organic carbon for 2021 and 2022 was 0.381 and 0.399 %, respectively. In contrast, the corresponding nitrogen content of the soil was 0.084 % and 0.056 %, Base saturation was 84.44% and 70.8% in the years 2021 and 2022, respectively, and Available phosphorus(P) was 4.66 and 7.46mg/kg in the year 2021 and 2022 respectively. The soil organic carbon was 0.381 and 399 % in 2021 and 2022, respectively.

Table 1: Initial Soil properties of the study site collected at 0–30 cm depth.

Pre–planting analysis	2021	2022
Clay (%)	6	7
Silt (%)	9	7
Sand (%)	43	41
Coarse sand (%)	42	45
Bulk density(Mg/m^3)	5.6	5.2
Total porosity (g/cm^3)	36.23	42.26
Hydraulic conductivity (cm^3/hr)	51.12	27.88
Organic matter (%)	0.656	0.688
Nitrogen (%)	0.084	0.056
Sodium (Cmolkg^{-1})	0.10	0.11
Potassium (Cmolkg^{-1})	0.18	0.19
Calcium (Cmolkg^{-1})	4.80	3.60
Magnesium (Cmolkg^{-1})	1.00	1.20
Cation Exchange Capacity (Cmolkg^{-1})	7.20	7.20
Base saturation (%)	84.44	70.83
Exchangeable Acidity (Cmolkg^{-1})	1.40	1.20
Available Phosphorus (mg/kg)	4.66	7.46
Sulphur (g/kg)	1. 55	1.62
pH (H_20)	5	4.4
pH (KCl)	1.69	1.53
Organic Carbon (%)	0.381	0.399

3.2 Effect of tillage variants and sulphur fertilization on the nitrogen content of the soil.

The result presented in Table 2 shows that tillage variants and sulphur fertilization significantly ($P < 0.05$) influenced the soil's nitrogen content at 30, 60 and 90 days after planting during the 2021 and 2022 seasons. All no-till+gypsum$_2$ plots had significantly higher N content than each corresponding no-till+gypsum$_0$ plot by 15-40 %. In 2021 at 30 DAP, The no-till+gypsum$_2$ (42 kg/ha) gave the highest soil nitrogen content (0.088%), followed by the till+gypsum$_1$ (21 kg/ha) 0.085%. However, plots treated with till+ gypsum$_2$ (0.082%) recorded a lower nitrogen content than the previous but higher than plots treated with no-till+gypsum$_1$ (0.075 %), till+no gypsum (0.079 %) and the control (0.074 %), respectively. Similarly, at 60 DAP, the same trend was observed as the highest nitrogen content was recorded in the plot treated with no-till+gypsum$_2$ (42 kg/ha).

At 90 DAP and 120 DAP, the highest soil nitrogen content (0.111-0.2960 %) was recorded in the plots treated with no-till+gypsum$_2$ (42 kg/ha), followed by the plot treated with no-till+gypsum$_1$ (21kg/ha). They were both significantly different from the till+no gypsum (0.075%) and the control plot (0.080 %) but not significantly different from plots treated with till+gypsum$_1$ (21 kg/ha) and till+gypsum$_2$ (42 kg/ha). The higher N content found in the No-till+ gypsum plot may be ascribed to the ability of no-tillage adoption to conserve more of the soil nitrogen fixed. Similarly, It can be deduced that applying sulphur improved the soil's nitrogen content. Sulphur availability is favourably connected to symbiotic nitrogen fixation (SNF) in nodulated legumes, and sulphur deficiency results in decreased nodulation, suppression of SNF, and slowed nodule metabolism.

Table 2: Effect of tillage variants and sulphur fertilization on the nitrogen content (%) of the soil

DAYS AFTER PLANTING (DAP)						
	30		60		90	
Treatments	2021	2022	2021	2022	2021	2022
NTG_0	0.0735	0.0840	0.0720	0.0670	0.0800	0.1020
NTG_1	0.0750	0.1220	0.2430	0.2070	0.1108	0.2050
NTG_2	0.0880	0.1400	0.2890	0.2940	0.1100	0.2230
TG_0	0.0785	0.0860	0.0760	0.0630	0.0750	0.0161
TG_1	0.0850	0.1210	0.0810	0.0720	0.0983	0.1090
TG_2	0.0820	0.1130	0.0810	0.0840	0.0875	0.1130
$F\text{-}LSD_{(0.05)}$	0.0111	0.0220	0.0200	0.0310	0.0281	0.1012

NS = No significant effect; NTG_0, NTG_1 and NTG_2 = No-till no gypsum; no-till gypsum$_1$ (21 kg/ha) and no-till gypsum$_2$ (42 kg/ha) TG_0, TG_1 and TG_2 = Till no gypsum, till gypsum$_1$ (21 kg/ha) and till gypsum$_2$ (42 kg/ha); $F\text{-}LSD_{(0.05)}$ = Fisher's Least Significant Difference at 0.05 probability level.

The improvement of nitrogenase biosynthesis and activity, the buildup of nitrogen-rich amino acids, and the increase in leghemoglobin, ferredoxin, ATP, and glucose in nodules contribute to the growth in nitrogen fixation, therefore, improvement of the N content of the soils with improved S content. According to the efficacy of the rhizobia-host plant symbiosis, the ability of the host plant to acquire N, the amount of accessible soil N, and environmental restrictions all play a role in the nitrogen fixation (BNF) process (Van Kessel and Hartley, 2000). However, due to the depreciation of natural resources and climate change, its long-term viability has been questioned (Hobbs and Gupta 2003). This has become the foundation for why most researchers are now advocating for no-tillage adoption. Unlike conventional tillage, no-tillage minimizes soil and nutrient losses through leaching and erosion (Shipitalo et al., 2000; Schillinger, 2001). This is in agreement with the findings in this study.

3.3 Effect of tillage variants and sulphur fertilization on the soil's sulphur content

The results in Table 3 demonstrate that the tillage variants and sulphur fertilization significantly ($P < 0.05$) influenced soil sulphur content relative to the control plot (no-till+no gypsum) at 30, 60 and 90 days after planting during the 2021 and 2022 planting seasons. The highest mean soil sulphur content (4.3 - 4.7 g/kg) at 30 DAP was found in plots treated with no-till + gypsum$_2$ (42 kg/ha) for both seasons. In both seasons, this was statistically higher than the untreated plots (no-till+no gypsum) by 62-63 %. The soil sulphur content in the till +gypsum$_2$ (42 kg/ha) for both seasons at 30 DAP ranged from 3.3 - 3.5 g/kg, whereas those from till +gypsum$_1$ (21 kg/ha) ranged from 3.1-3.3 g/kg soil sulphur content. At 60 DAP, the highest mean soil sulphur content (4.2-4.6 g/kg) was found in plots treated with no-till +gypsum$_2$ (42 kg/ha) for both seasons, followed by plots treated with no-till+gypsum$_1$ (21 kg/ha) with 3.3-3.5 g/kg, then till+no gypsum plots and no till+no gypsum plots with 1.5-1.8 g/kg mean soil sulphur content. The results also followed the same trend, with plots treated with no-till + gypsum$_2$ (42 kg/ha) having statistically higher soil sulphur content relative to no-till +no gypsum and till +no gypsum plots DAP. The results also showed that the values for soil sulphur content of no-till +gypsum$_2$ and no-till +gypsum$_1$ and between till +gypsum$_2$ and till +gypsum$_1$ were statistically the same. These study results infer that sulphur is an integral and necessary nutrient component for a better yield of Bambara groundnut.

Table 3: Effect of tillage variants and sulphur fertilization on the sulphur content (g/kg) of the soil

	DAYS AFTER PLANTING (DAP)					
	30		60		90	
Treatments	2021	2022	2021	2022	2021	2022
NTG_0	1.6	1.8	1.4	1.4	1.2	1.0
NTG_1	3.6	4.1	3.9	3.5	3.3	4.0
NTG_2	4.3	4.7	4.2	4.6	4.5	4.2
TG_0	1.3	1.6	1.8	1.5	1.4	1.0
TG_1	3.1	3.3	3.1	3.6	3.2	3.8
TG_2	3.3	3.5	3.7	3.8	3.4	3.7
F-LSD$_{(0.05)}$	1.2	1.4	1.0	1.2	1.1	1.9

NS = No significant effect; NTG_0, NTG_1 and NTG_2 = No-till no gypsum; no-till gypsum$_1$ (21 kg/ha) and no-till gypsum$_2$ (42 kg/ha) TG_0, TG_1 and TG_2 = Till no gypsum, till gypsum$_1$ (21 kg/ha) and till gypsum$_2$ (42 kg/ha); F-LSD$_{(0.05)}$ = Fisher's Least Significant Difference at 0.05 probability level.

However, according to sulphur deficiency significantly affects the production and quality of the crop (Zhao et al., 1990; McGrath, 2003; Györi, 2005). Without adequate sulphur, crops can neither reach their full potential in yield, quality, or protein content nor use applied nitrogen efficiently (Sahota, 2006). The variation in sulphur content found in the different plots in this study could be attributed to the different tillage methods and soil amendment with gypsum ($CaSo_4$) adopted and in which no-tillage and conventional tillage practices with the sulphur application were used. However, in the 2022 planting season, no-till+gypsum (soil treated with sulphur) gave the highest significant sulphur content. According to soil fertility often changes in response to land use and, cropping systems and land management practices (Tesfahunegn and Gebru, 2020).

Adequate sulphur nutrition improves photosynthesis and the growth of plants and has regulatory interactions with nitrogen assimilation (Scherer, 2008). Sulphur is required for protein synthesis and nitrogen assimilation and is a structural constituent of several coenzymes and prosthetic groups (Hawkesford et al., 2012). Nitrogen fixation may be reduced under sulphur-deficient conditions because of nitrogen accumulation resulting from the reduced rate of protein synthesis. Consequently, nitrogenase activity is retarded, resulting in low nitrogen fixation (Scherer, 2008).

3.4 Effect of tillage variants and sulphur fertilization on nodule count of Bambara groundnut

Results of the study in Table 4 show that the treatment application significantly affected the number of nodules per plant of Bambara groundnuts at 30 DAP in the first and second seasons. The highest mean number of nodules per plant at 30 DAP (25-26) was found in plots treated with no-till +gypsum$_2$ (42 kg/ha) for both seasons. In both seasons, this was statistically higher than the untreated plots (no-till+no gypsum) by 72-74 %. The number of nodules per plant in the no till +gypsum$_1$ (21 kg/ha) for both seasons at 30 DAP ranged from 23-24, whereas those from till +gypsum$_2$ (42 kg/ha) ranged from 18-20 nodules per plant. At 60 DAP, the highest mean number of nodules per plant (29-30) was found in plots treated with no-till + gypsum$_2$ (42 kg/ha) for both seasons. In both seasons, this was statistically higher than the untreated plots (no-till+no gypsum) by 60-62 %. The plots treated with no-till+gypsum$_1$ (21 kg/ha) had 27-28 nodules per plant, and till+no gypsum plots and no till+no gypsum plots with 11-12 nodules per plant. However, at 90 DAP, no significant treatment effect was observed among the treatment means.

Table 4: Effect of tillage variants and sulphur fertilization on nodule count per plant

	DAYS AFTER PLANTING (DAP)					
	30		60		90	
Treatments	2021	2022	2021	2022	2021	2022
NTG_0	7.00	7.20	10.80	11.50	3.30	3.80
NTG_1	23.40	23.90	26.50	27.50	14.00	15.00
NTG_2	24.90	26.50	28.50	29.50	15.20	16.20
TG_0	9.90	10.90	11.00	12.00	8.00	9.00
TG_1	11.20	11.90	13.00	16.50	9.00	10.00
TG2	18.40	19.50	17.80	18.80	9.50	10.50
F-LSD$_{(0.05)}$	3.56	4.22	4.04	2.64	NS	NS

NS = No significant effect; NTG_0, NTG_1 and NTG_2 = No-till no gypsum; no-till gypsum$_1$ (21 kg/ha) and no-till gypsum$_2$ (42 kg/ha) TG_0, TG_1 and TG_2 = Till no gypsum, till gypsum$_1$ (21 kg/ha) and till gypsum$_2$ (42 kg/ha); F-LSD$_{(0.05)}$ = Fisher's Least Significant Difference at 0.05 probability level.

This study shows that no-tillage and sulphur application positively influenced the nodule formation of Bambara groundnut. This is likely to increase nitrogen fixation. If few or small nodules are present, sufficient soil nitrogen may not be available for the young plant before nitrogen fixation. This is aligned with the findings of (Mhango et al., 2008). Sulphur is essential in nitrogen fixation and legume production because it is essential in nodule formation, a significant nitrogenase component and growth. It was reported that liming with calcium sulphate (Gypsum) significantly increased nodule number, nodule volume, and nodule dry weight per plant compared with the unlimed and non-inoculated treatments (Anderson et al., 2020). Calcium sulphate is suitable for plants, but no one considers it an essential source of plant nutrients. In addition, it is also a natural source of calcium and sulphur for plant nutrition, both of which are secondary macronutrients.

3.5 Effect of tillage variants and sulphur fertilization on nodule effectivity count

Table 5: Effect of tillage variants and sulphur fertilization on effective nodule count

	DAYS AFTER PLANTING (DAP)					
	30		60		90	
Treatments	2021	2022	2021	2022	2021	2022
NTG_0	2.50	5.20	5.00	6.30	2.50	3.20
NTG_1	17.90	20.10	19.80	20.80	6.50	9.00
NTG_2	23.80	25.00	21.50	22.50	9.50	10.50
TG_0	8.00	9.20	7.00	7.80	5.00	5.00
TG_1	9.90	10.40	7.00	8.00	5.20	6.00
TG_2	16.80	19.00	11.50	12.50	8.00	7.50
F-LSD$_{(0.05)}$	1.95	2.49	1.74	1.77	NS	NS

NS = No significant effect; NTG_0, NTG_1 and NTG_2 = No-till no gypsum; no-till gypsum$_1$ (21 kg/ha) and no-till gypsum$_2$ (42 kg/ha) TG_0, TG_1 and TG_2 = Till no gypsum, till gypsum$_1$ (21 kg/ha) and till gypsum$_2$ (42 kg/ha); F-LSD$_{(0.05)}$ = Fisher's Least Significant Difference at 0.05 probability level.

Results of the study in Table 5 show that the treatment application significantly affects the number of effective nodules per plant of Bambara groundnuts at 30 DAP in the first and second seasons. The highest mean number of effective nodules per plant at 30 DAP (23-25) was found in plots treated with no-till + gypsum$_2$ (42 kg/ha) for both seasons. In both seasons, this was statistically higher than the untreated plots (no-till+no gypsum) by 79-89 %. The number of effective nodules per plant in the till +gypsum$_2$ (42 kg/ha) for both seasons at 30 DAP ranged from 17-19, whereas those from till +gypsum$_1$ (21 kg/ha) ranged from 9-10 effective nodules per plant. At 60 DAP, the highest mean number of effective nodules per plant (22-23) was found in plots treated with no-till +gypsum$_2$ (42 kg/ha) for both seasons, followed by plots treated with no-till+gypsum$_1$ (21 kg/ha) with 20-21 effective nodules per plant, then till+no gypsum plots and no till+no gypsum plots with 6-8 number of effective nodules per plant. However, at 90 DAP, no significant treatment effect was observed among the treatment means. The result showed that no-tillage and gypsum application had a more significant effect on effective nodulation, which is in line with the earlier report by (Anikwe et al., 2016). The deficiency of phosphorous, potassium and sulphur also compromises nitrogen fixation in legumes, including field peas, as reviewed by (Scherer et al., 2008; Divito and Sadras, 2014).

3.6 Effect of tillage variants and sulphur fertilization on leaf area index

The results in Table 6 show a significant difference in the leaf area index at different days after planting in both planting seasons, except at 120 DAP in 2021. During the 2021 planting season at 30 DAP, plots treated with no-till+gypsum$_2$ (42 kg/ha) gave the highest leaf area index (1.166), which increased relative to other treated plots by 35-75%. At 60 DAP plots treated with no-till gypsum$_2$ (42 kg/ha) recorded the highest leaf area index (5.05) of Bambara groundnut, which increased by 29-53% relative to all other plots. At 90 DAP, no significant differences were found among the treatment means.

Table 6: Effect of tillage variants and sulphur fertilization on leaf area index

	DAYS AFTER PLANTING (DAP)					
	30		60		90	
Treatments	2021	2022	2021	2022	2021	2022
NTG$_0$	0.3470	0.6840	2.4000	2.5700	2.2700	2.5100
NTG$_1$	0.8680	1.2630	3.8400	3.0400	5.7400	6.5500
NTG$_2$	1.1660	1.3670	5.0500	5.4500	7.4500	7.920
TG$_0$	0.7360	0.7830	3.3500	4.0100	5.0200	7.1200
TG$_1$	0.5270	1.0820	3.7500	3.7600	5.1300	7.1800
TG$_2$	0.7760	1.0930	3.4400	3.3200	5.7000	7.3500
F-LSD$_{(0.05)}$	0.1151	0.4659	0.9600	1.8990	1.5450	2.6070

NS = No significant effect; NTG$_0$, NTG$_1$ and NTG$_2$ = No-till no gypsum; no-till gypsum$_1$ (21 kg/ha) and no-till gypsum$_2$ (42 kg/ha) TG$_0$; TG$_1$ and TG$_2$ = Till no gypsum, till gypsum$_1$ (21 kg/ha) and till gypsum$_2$ (42 kg/ha); F-LSD$_{(0.05)}$ = Fisher's Least Significant Difference at 0.05 probability level.

In the 2022 planting season at 30 DAP, Bambara groundnut in the plot treated with no-till gypsum$_2$ (42 kg/ha) had the highest leaf area index (1.367), higher than that LAI of all other plots by 13-51%. At 60 DAP, the plot treated with no-till+gypsum$_2$ (42 kg/ha) gave the highest leaf area index (3.45) of Bambara groundnut, which increased by 29-52 % compared to all other plots. At 90 DAP, the plot treated with no-till+gypsum$_2$ (42 kg/ha) with LAI of 7.95 gave a higher leaf area index of Bambara groundnut, which showed an increase of 57-69 % when compared with that of all the other plots. From this result, sulphur fertilization and zero tillage positively affected the vegetative feature of Bambara groundnut. Sulphur is also an essential component of ferredoxin, an iron- sulphur protein found in chloroplasts. Ferredoxin aids in reducing nitrogen dioxide and sulphate, the assimilation of N-root nodule bacteria, and liberating living N-fixing soil bacteria (Scherer et al., 2020). All these resulted in increased growth and yield of Bambara groundnuts.

3.7 Effect of tillage variants and sulphur fertilization on seed weight (yield) (t/ha)

The results in Table 7 show that tillage variants and sulphur fertilization significantly influenced the seed yield during the 2021 planting season. During the first planting season, the results showed significant treatment differences in grain yield weight among the treatment means. The plots treated with no-till+gypsum$_2$ (42 kg/ha) had the highest yield (0.94 t/ha), followed by the plots treated with no-till+gypsum$_1$ (42 kg/ha) with 0.93 t/ha dry seed yield and till+gypsum$_2$ (42 kg/ha) which was higher (P<0.05) than that of the control plot by 54-55% respectively. No significant treatment differences were found between the LAI and seed weight yield between No-Till+Gypsum$_2$ and No-till gypsum$_1$, probably because S exerted more influence on the yield of the crop. The sufficiency of S in tropical soils ranges from 2.0-4.0 g/kg (Scherer, 2008); beyond that, the response may be unlikely. Average yields of dry seeds usually range between 0.30 and 0.80 t/ha in traditional farming and may exceed 3 t/ha in intensive agriculture (Baudoin and Mergeai 2001). A group researcher also reported 0.5–1.000 tonne of dried nuts per hectare yields (Williams et al., 1979). Gibbon and Pain observed that products are lower than groundnuts, 0.3–0.8 t/ha being average in most northern parts of Ghana (Gibbon and Pain, 1985). It can be deduced from this result that both no-tillage practices and sulphur application positively influenced the yield of Bambara groundnut.

Table 7: Effect of tillage variants and sulphur fertilization on seed weight (t/ha).

Treatment	2021	2022
NTG$_0$	0.3885	0.4399
NTG$_1$	0.9292	0.9784
NTG$_2$	0.9350	0.9852
TG$_0$	0.4329	0.4837
TG$_1$	0.4308	0.4841
TG$_2$	0.6110	0.6612
F-LSD$_{(0.05)}$	0.1781	0.1581

NS = No significant effect; NTG$_0$, NTG$_1$ and NTG$_2$ = No-till no gypsum; no-till gypsum$_1$ (21 kg/ha) and no-till gypsum$_2$ (42 kg/ha) TG$_0$; TG$_1$ and TG$_2$ = Till no gypsum, till gypsum$_1$ (21 kg/ha) and till gypsum$_2$ (42 kg/ha); F-LSD$_{(0.05)}$ = Fisher's Least Significant Difference at 0.05 probability level.

3.8 Relationship between Bambara groundnut yield and some soil properties as influenced by tillage variants and sulphur fertilization

Because of the central role of S and N in synthesizing proteins, the supply of these nutrients in plants is highly interrelated. The results in Table 8 show a positive, highly significant relationship between dry seed weight and percentage sulphur content in the 2021 and 2022 planting seasons, with a recorded value of r=0.97** and r=0.91**. Similarly, the soil percentage nitrogen content significantly and positively correlated with Bambara groundnut yield (seed weight) in 2021 years, recording a value of (r=0.87*). It was also positively correlated in 2022 with a recorded value of (r=0.684*). Nitrogen and sulphur ratio had a positive relationship with yield (seed weight) as influenced by tillage variants and sulphur fertilization with a recorded value of (r=0.60*) and (r=0.50*) during the 2021 and 2022 planting seasons, respectively. In terms of dry matter and yield in several crops, sulphur and nitrogen relationships were established in many studies (McGrath and Zhao, 1996; Jamal and Zainul, 2010).

Table 8: Relationship between Bambara groundnut yield and some soil physicochemical properties as influenced by tillage variants and sulphur fertilization (Correlation, r)

Soil properties	2021	2022
Sulphur (SO_4)	0.966**	0.912**
Nitrogen (N)	0.874**	0.684*
N: SO_4	0.604*	0.500*

* = Highly significant at P=0.05

** = Significant at P=0.05

4. Conclusion

The findings of this study show that during the two planting seasons of Bambara groundnut (*Vigna subterranean),* no-tillage and gypsum application enhanced a higher number of nodulation, percent nitrogen, and sulphur content in the soil. Sulphur is essential in nitrogen fixation and legume production because it is essential in nodule formation, a significant component of nitrogenase and growth. The no-till gypsum$_2$ (42 kg/ha) plot gave the highest yield of 0.94 t/ha, which was followed by the no-till gypsum$_1$ (21 kg/ha) had a recorded value of 0.93 t/ha and till gypsum$_2$ (42 kg/ha) had a value of 0.61 t/ha. The study indicated that soils under no-tillage were not disturbed and remained intact. No-tilled plots also conserved nutrients and water. The dry matter yield was highest with a high S supply at both S increments and the no-till system. The high S application rate resulted in a significantly higher N accumulation, mainly caused by a higher N2 fixation rate. With the grain legumes, the number of nodules was increased by the high S application rate. The higher number of nodules per plot with optimum S supply resulted from better root growth. Rates of increase in the number and effectivity of nodules correlated significantly with S supply and no-tillage.

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