Journal of Agriculture, Forestry and Environment, 2026, 10 (1):224-237
A publication of Faculty of Agriculture, University of Calabar, Calabar
ISSN: 2141-9965

RESPONSE OF GROUNDNUT (*Arachis hypogaea L.*) TO VARYING RATES OF SULPHUR APPLICATION AND EVALUATION OF SULPHUR EXTRACTANTS IN SELECTED SOILS OF NASARAWA STATE

***[1]Muhammad K. Ndagana, [2]Moses B. Dang and [3]Sani Abdullahi**
[1]Department of Crop and Forestry,
NAERLS/ABU Zaria, Kaduna State
[2]Department of Soil Science
Federal University Lafia, Nasarawa State
[3]Department of Agricultural Technology
College of Agriculture, Mokwa
**Corresponding author email: kolomuhammad3@gmail.com*

Abstract
Sulphur (S) deficiency is becoming increasingly important in Nigerian soils, yet information on S status in Nasarawa State remains limited. This study evaluated groundnut (*Arachis hypogaea* L.) response to varying S rates and assessed S extractants in six soils of Nasarawa State. Laboratory analysis, pot experiments (0, 10, 20, 30, 40 kg S ha^{-1} as K_2SO_4), and field observations were conducted using standard procedures. Soils were slightly acidic to neutral (pH 5.82–6.68), with low organic matter (1.34–1.85%) and sandy loam textures. Total S ranged from 15.61–68.83 mg kg^{-1}, while KH_2PO_4-extractable S varied from 0.23–1.06 mg kg^{-1}. Groundnut responded significantly ($p<0.01$) to S application, with optimal rates varying from 10–40 kg S ha^{-1} depending on soil type and yield parameter. Fresh biomass (43.10–116.15 g pot^{-1}), pod weight (8.85–36.10 g $plant^{-1}$), pod number (10.00–28.50 $plant^{-1}$), and seed weight (2.30–7.85 g $plant^{-1}$) increased with S application. Field yields ranged from 0.49–0.85 t ha^{-1}. Correlation analysis revealed that 0.016 M KH_2PO_4 extractable S showed the most significant positive correlation with yield parameters ($r=0.21–0.36$), followed by 0.010 M LiCl, establishing it as the most suitable extractant. The critical S level for groundnut production was established at 0.24 and 0.23 mg kg^{-1} KH_2PO_4-extractable S. This study recommends S fertilization for soils with KH_2PO_4-extractable S below 0.24 and 0.23 mg kg^{-1}, adoption of crop residue management to conserve organic matter, and discouragement of bush burning practices in Nasarawa State.

Keywords: Groundnut, sulphur extractants, sulphur fertilization, Nasarawa soils, critical level

Introduction

Sulphur (S) as a yield-limiting nutrient factor is becoming increasingly important in many Nigerian soils. Occurrences of deficiency in various crops are becoming more frequent and extensive (Kang *et al*., 2009; Adetunji and Adepetu, 2010; Obasi *et al*., 2023). Soil sulphur studies in Nigeria were pioneered by Greenwood (2019) and popularized by Bromfield (2021). Most of their studies were on groundnut and other legume crops in Northern Nigeria where they obtained significant response to the applications of sulphur by the crops studied. Since then, other workers (Kang *et al*., 2010; Adetunji and Adepetu, 2012; Enwezor, 2019; Obasi *et al*., 2023) have reported responses of various crops in other agro-ecological zones of Nigeria to the application of sulphur.

Groundnut (*Arachis hypogaea L.*) is one of the cash crops grown in Nasarawa State. It is normally grown in rotation to improve the soil nutrients because of its ability to fix nitrogen. It is preferred to rice because of its relatively low labour in terms of weeding and the perennial problem of birds experienced in rice production. Apart from being a cash crop, it is consumed in large quantities in various forms and serves as one of the major sources of dietary protein. Sulphur is a constituent of methionine, cysteine, and all of which are essential amino acids (Hawkesford, 2012). In the past, it was being added to the soil through the application of single superphosphate which apart from supplying phosphorus also contains about 23% sulphur and through sulphate of ammonium which contains more than 20% sulphur (Scherer, 2001). However, with the increase in the use of high analysis fertilizers, many sulphur-free fertilizers are now available in the market. Moreover, sulphur-containing pesticides that were commonly used in the past have largely been replaced by organic materials free of sulphur. Nevertheless, the practice of slash and burn agriculture which leads to sulphur loss is still very common among the people (Brady and Weil, 2016).

Despite all these, the general assumption that sulphur deficiency is not widespread and therefore does not constitute a significant problem to crop yield still persists. This may be particularly so in many Nigerian soils, especially where information on sulphur status is unavailable. Nasarawa State falls in that category. More work is required in order to accurately predict sulphur needs of various crops in different ecological zones of Nigeria (Sharma *et al*., 2018; Devi *et al*., 2021). Therefore, this study evaluated response of groundnut to different rates of S application and evaluates S extractants in selected soils of Nasarawa State.

Materials and methods

Experimental Site

The experiments involved laboratory studies, pot experiment, and field observation. Surface soil samples (0-15 cm) were collected from six sites namely: Awonge, Kawo, Doma North, Burum-Burum Road site, Alwaza Waje, and Alwaza Town on the groundnut producing area of Nasarawa State that have no previous history of S fertilization.

Laboratory Analysis

Subsamples of the soils were sieved to pass 2 mm sieve for laboratory and pot experiments. The samples were analysed for the physical and chemical parameters using standard procedures (Page *et al*., 1982; Motsara and Roy, 2008). Four extractants were evaluated for the determination of available sulphur. These were distilled water, 0.010 M LiCl, 0.016 M KH_2PO_4, and 0.010 M $Ca(HPO_4)_2$. Each extractant was employed for the extraction of available S in all the samples. Sulphur solution or water-soluble sulphur was extracted in distilled water and determined turbidimetrically as $BaSO_4$. Surface adsorbed S was estimated as the difference between available S and water-soluble S. Available S was taken as the 0.016 M KH_2PO_4 extractable S. Total soil S was determined by digesting the samples using wet acid digestion (Page *et al*., 1982); activated charcoal, 0.05 g per 25 cm^3 of the extracts and digest was used for decolorizing the extracts and/or digest; while gelatin was used as a stabilizer. Sulphur in the extracts and/or digest was determined turbidimetrically as $BaSO_4$ (Bardsley & Lancaster, 1960; Anjembe & Adetunji, 2022).

Pot Experiment

Subsamples of the sieved soils (4 kg) were weighed into 20 cm diameter experimental pots. Five levels of sulphur (0, 10, 20, 30, and 40 kg S ha^{-1}) were added as K_2SO_4. The treatments were replicated three times and pots were arranged in a completely randomized design.

The local variety (Ada-mma) of groundnut which is upright and early maturing was sown on the 11th June, 2023 and harvested on the 10th September, 2023 (12 weeks after planting). Agronomic data (i.e. fresh biomass, fresh weight of pods, number of pods) were collected and analysed to determine the response of groundnut to S application. The yield parameters were measured at harvest as seed weight.

Field Observation

Six locations' fields cultivated with groundnuts as a sole crop were selected to verify the findings of the pot experiment. On each location, an area of land covering 5 m × 5 m was measured. Yield of groundnut from that area was collected and weighed. The soil sample taken from that area was analysed for extractable sulphur using the four extractants. The sulphur values were then correlated with the yield of groundnuts.

Data Analysis

Data collected were subjected to analysis of variance (ANOVA) using SAS software (version 9.4) to test the significance of the treatment effects on the response of the crop in the pot and observation in the locations. Treatment means were compared using Fisher's Least Significant Difference (LSD) at $p<0.05$. The amount of available sulphur extracted by the four extractants was correlated with the groundnut yield of experiment soil with the aim of determining the best extractant using Pearson's correlation coefficient.

Results and discussion

Properties of the experimental soil

The properties of the soils investigated in the study are shown in Table 1. The pH ranged from 5.82 at Awonge to 6.68 at Burum-Burum Road with a mean value of 6.38 indicating slightly acidic to neutral conditions, which are generally favorable for groundnut production. The optimum pH range for groundnut cultivation is between 5.5 and 7.0 (Singh *et al*., 2019; Reddy *et al*., 2021). Clay content ranged from 9.8% at Awonge and Burum-Burum Road to 13.8% at Doma North, Alwaza Town, and Alwaza Waje. The low clay content (9.8-13.8%) and predominantly loamy sand to sandy loam textures suggest that these soils have limited capacity for nutrient retention and are susceptible to leaching losses (Brady & Weil, 2016). This finding is consistent with reports by Jones *et al*. (2017) who noted that sandy soils in tropical regions typically exhibit low nutrient holding capacities.

Organic matter content varied widely from 1.34% at Burum-Burum Road site to 1.85% at Doma North with a mean value of 1.53%. The organic matter content (1.34-1.85%) is generally low, which is characteristic of tropical soils subjected to continuous cultivation and bush burning (Lal, 2015; Obalum *et al*., 2017). Organic matter serves as the primary reservoir of soil sulphur, and its low content partly explains the low total sulphur status of these soils (Scherer, 2001; Eriksen, 2009). The significant relationship between soil organic matter and sulphur content observed in this study corroborates findings by Ghosh *et al*. (2016) and Kumar *et al*. (2018) who reported strong positive correlations between these parameters in tropical soils.

Total nitrogen ranged from 0.14% at Awonge to 0.28% at Alwaza Waje and Burum-Burum Road with a mean value of 0.22%. Available phosphorus (P) values ranged from 3.32 mg kg^{-1} at Alwaza Town to 3.62 mg kg^{-1} at Doma North with a mean value of 3.41 mg kg^{-1}. Exchangeable acidity ranged from 0.33 cmol kg^{-1} at Doma North to 1.66 cmol kg^{-1} at Kawo. Cation exchange capacity varied from 4.78 cmol kg^{-1} at Kawo to 6.35 cmol kg^{-1} at Awonge.

Table 1: Some Properties of the Experimental Soils

Location	pH (H_2O)	Clay %	O. M %	N %	Av. P (mg/kg)	Ca ←	Mg	Na cmol/kg	K	E.A →	CEC
Awonge	5.82	9.8	1.51	0.14	3.45	3.82	2.11	0.11	0.31	0.83	6.35
Kawo	6.41	11.8	1.41	0.21	3.38	2.38	1.89	0.23	0.28	1.66	4.78
Doma North	6.47	13.8	1.85	0.21	3.62	2.43	2.01	0.21	0.35	0.33	5.03
B/B Road	6.68	9.8	1.34	0.28	3.32	2.35	2.03	0.23	0.34	1.50	4.91
Alwaza Town	6.52	13.8	1.65	0.21	3.28	2.38	1.98	0.28	0.29	0.83	4.98
Alwaza Waje	6.40	13.8	1.44	0.28	3.41	2.56	2.00	0.30	0.32	0.50	5.10
Mean	6.38	12.1	1.53	0.22	3.41	2.65	2	0.23	0.32	0.94	5.19

Note: B/B Road: Burum-Burum Road; O.M = Organic Matter, E.A = Exchangeable Acidity, CEC = Cation Exchange Capacity

Sulphur Fractions of the Experimental Soils

Amount of S extracted by the various Extractants in the locations are shown in Table 2. The total S values ranged from 15.61 mg kg^{-1} at Kawo to 68.83 mg kg^{-1} at Alwaza Town. Potassium hydrogen phosphate-extractable S varied from 0.23 mg kg^{-1} at Burum-Burum Road to 1.06 mg kg^{-1} at Alwaza Waje. Water-soluble sulphur varied from 0.98 mg kg^{-1} at Awonge to 49.81 mg kg^{-1} at Burum-Burum Road. On the average, water-soluble S constituted about 28.13% of the total soil S, LiCl-extractable S constituted 10.58% of the total S, and Ca $(HPO_4)_2$-extractable S constituted 0.50% of the total sulphur.

The total sulphur content (15.61-68.83 mg kg^{-1}) is generally low compared to the critical level of 100-200 mg kg^{-1} reported for optimal

Journal of Agriculture, Forestry and Environment, 2026, 10 (1):224-237
A publication of Faculty of Agriculture, University of Calabar, Calabar
ISSN: 2141-9965

crop production in tropical soils (Adetunji & Adepetu, 2010; Shamim *et al*., 2016). However, these values are within the range (10-100 mg kg^{-1}) reported for Nigerian soils by Enwezor (2019) and Kang *et al*. (2022). The low total S status can be attributed to continuous cropping without adequate sulphur replenishment, losses through leaching due to sandy texture, and losses through volatilization during bush burning (Tandon, 2018; Bromfield, 2021).

The water-soluble S values varied widely (0.98-49.81 mg kg^{-1}), constituting 28.13% of total S on average. This is consistent with findings by Maynard *et al*. (2023) who reported that water-soluble S typically accounts for 20-40% of total soil S in tropical soils. The high proportion of water-soluble S in some soils (Burum-Burum Road, Doma North) suggests that S is present mainly in readily available forms, which is beneficial for immediate crop uptake (McGrath *et al*., 2002; Zhao *et al*., 2019).

The KH_2PO_4 extractable-S (0.23-1.06 mg kg^{-1}) was substantially lower than the 6.7 mg kg^{-1} reported by Adetunji (2022) for other Nigerian soils. This could be attributed to the low organic matter content and the intensive cropping history of these soils.

Table 2: Amount of S Extracted by the Various Extractants in the Experimental Soils (mg kg^{-1})

Location	Extractants				
	Water	0.010M LiCl	0.010M $Ca(HPO_4)_2$	0.016M KH_2PO_4	Total S
Awonge	0.98	14.86	0.59	0.69	17.12
Kawo	3.87	10.66	0.84	0.24	15.61
Doma North	49.07	12.30	1.42	0.29	63.08
Burum-Burum Road	49.81	3.63	1.16	0.23	54.83
Alwaza Town	43.58	20.86	3.43	0.96	68.83
Alwaza Waje	46.52	10.57	1.33	1.06	59.48
LSD ($p<0.05$)	0.03	0.03	0.04	0.02	0.01

Effects of Sulphur Rates on Fresh Groundnut Biomass

At Awonge, the highest fresh weight of biomass (116.15 g) was obtained when 40 kg ha^{-1} was applied, compared to the other treatments (Table 3). In Kawo area, the 10 kg ha^{-1} S treatment produced the highest fresh biomass of 58.85 g, which was significantly greater ($p<0.01$) than the other treatments applied. However, in Doma North, the highest fresh biomass of 77.55 g was obtained when 40 kg ha^{-1} of S was applied to the soil in the pot, and this was significantly different ($p<0.01$) from the other treatments. Burum-Burum Road recorded the highest fresh biomass yield of 80.60 g when 20 kg ha^{-1} S was applied to the soil. The least biomass, 57.25 g, was recorded in the control. Application beyond 20 kg ha^{-1} S progressively decreased the biomass yield at this location. At Alwaza Town, 30 kg ha^{-1} S had the highest biomass of 63.35 g, which was significantly higher ($p<0.01$) than 20 kg ha^{-1} S and the least value of 55.50 g was obtained from 40 kg S ha^{-1}. Similar trend of result was observed at Kawo and Alwaza

Waje when 10 kg S ha^{-1} was applied to the soil producing the highest fresh weight of biomass (66.35 g) significantly higher than other treatments applied at the locations.

The significant response of groundnut biomass to sulphur application across all locations is consistent with findings by Singh *et al*. (2020) and Devi *et al*. (2021) who reported that S application enhances vegetative growth in legumes. Sulphur plays a crucial role in chlorophyll formation and protein synthesis, which directly influences biomass accumulation (Hawkesford, 2012; Naeem *et al*., 2018).

The differential response to S rates among locations reflects the initial soil S status and other soil properties. For instance, Awonge soil, despite having low total S (17.12 mg kg^{-1}), showed the highest biomass yield at 40 kg S ha^{-1}, indicating severe S deficiency. This is similar to findings by Sharma *et al*. (2018) who observed that soils with low indigenous S supply require higher fertilizer rates for optimal growth.

The decline in biomass yield at higher S rates in some locations (Kawo, Burum-Burum Road, Alwaza Town) suggests that excessive S application can be detrimental. This could be due to ionic imbalance, antagonistic effects with other nutrients, or salt injury (Fageria *et al*., 2011; Choudhary *et al*., 2019). The optimum S rate varied among locations, highlighting the need for site-specific S fertilizer recommendations (Tandon, 2018; Singh *et al*., 2020).

The relatively poor biomass yields in Kawo (38.70-58.85 g) compared to other locations can be attributed to its low organic matter content and the highest exchangeable acidity (1.66 cmol kg^{-1}), which may have limited nutrient availability and root development (Kumar *et al*., 2018; Obalum *et al*., 2017).

Table 3: Effects of Sulphur on the Fresh Groundnut Biomass (g pot $^{-1}$) in the Pot Experiment

Sulphur (kg/ha)	Awonge	Kawo	Doma North	Burum-Burum	Alwaza-town	Alwaza-waje
0	76.10±0.60^{c}	38.70±0.50^{d}	67.15±0.35^{b}	57.25±0.05^{c}	61.35±0.05^{ab}	45.10±0.40^{e}
10	66.05±0.35^{d}	58.85±0.55^{a}	66.25±0.45^{b}	67.30±0.50^{c}	58.95±0.55^{bc}	66.35±0.45^{a}
20	76.50±0.50^{c}	45.65±0.05^{c}	43.10±0.40^{c}	80.60±0.60^{a}	55.00±0.00^{c}	50.00±0.20^{d}
30	85.00±1.00^{b}	54.41±1.38^{b}	64.60±0.80^{b}	74.55±0.85^{b}	63.35±0.15^{a}	60.85±0.15^{b}
40	116.15±0.35^{a}	57.00±1.00^{ab}	77.55±1.75^{a}	61.90±0.40^{d}	55.50±2.50^{c}	54.85±1.55^{c}
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Means on the same column with different superscripts are statistically significant (p<0.01).

Effects of Sulphur Rates on Fresh Weight of Pods

Fresh weight of pods obtained in the experimental soils is shown in Table 4. At Awonge, the highest pod yield of 23.00 g was obtained when 10 kg S ha^{-1} was applied to the soil. This was significantly different from all the other treatments at this location. Increasing the sulphur rate beyond 10 kg S ha^{-1} progressively reduced the pod yield. At Kawo, application of 20 kg S ha^{-1} produced the highest pod yield of 16.50 g. Application beyond 20 kg S ha^{-1} significantly reduced the pod yield at this location. In Doma North, the highest pod yield of 36.10 g was obtained when 10 kg S ha^{-1} was applied to the soil. This was significantly different from the other treatments applied (20, 30, and 40 kg S ha^{-1}). Increasing the sulphur rate beyond 10 kg S ha^{-1} significantly decreased ($p<0.05$) the pod yield at the location. Meanwhile, at Burum-Burum Road, 21.80 g was recorded when 30 kg S ha^{-1} was applied. At Alwaza Town, a pod yield of 17.20 g was obtained when 10 kg ha^{-1} was applied. But in Alwaza Waje area, 20 kg ha^{-1} S produced the greater pod yield of 16.60 g. This was significantly different from all the other treatments applied. Application beyond this rate (20 kg S ha^{-1}) significantly reduced the pod yield at this location.

The significant increase in pod yield with S application is consistent with the findings of Singh *et al*. (2019) and Reddy *et al*. (2021) who reported that S plays a critical role in pod development in groundnut. Sulphur is essential for the synthesis of S-containing amino acids (methionine and cysteine) which are crucial for seed protein formation (Scherer, 2001; Naeem *et al*., 2018).

The highest pod yield at Doma North (36.10 g) with 10 kg S ha^{-1} can be attributed to its relatively higher organic matter content (1.85%) and clay content (13.8%), which provided better S retention and availability (Eriksen, 2009; Zhao *et al*., 2019). This finding aligns with observations by Kumar *et al*. (2018) that soils with higher organic matter support better crop response to applied S due to sustained mineralization.

The decline in pod yield at higher S rates in most locations indicates that the optimal S requirement for groundnut pod production is relatively low. This is consistent with findings by Sharma *et al*. (2018) and Devi *et al*. (2021) who reported that groundnut requires 10-20 kg S ha^{-1} for optimum pod yield. The reduced yield at higher S rates could be due to nutrient antagonism, particularly with molybdenum and zinc, which are essential for nitrogen fixation and pod development (Fageria *et al*., 2011; Choudhary *et al*., 2019).

The relatively poor pod yield in Kawo, Alwaza Town, and Alwaza Waje soils (8.85-17.20 g) reflects their low indigenous S status and poor soil fertility. This is similar to findings by Adetunji and Adepetu (2010) and Obasi *et al*. (2023) who reported that soils with low organic matter and clay content exhibit poor crop response to applied nutrients.

Table 4: Effects of Sulphur Rates on the Fresh Weight of Pods (g/plant) in Pot Experiment

Sulphur (kg/ha)	Awonge	Kawo	Doma North	Burum-Burum	Alwaza-town	Alwaza-waje
0	17.50± 050^{b}	11.50±0.50^{b}	14.70±0.50^{c}	14.75±0.05^{c}	12.80±0.40^{b}	12.00±0.50^{c}
10	23.00±1.00^{a}	12.50±0.50^{b}	36.10±0.40^{a}	12.05±0.25^{d}	17.20±0.30^{a}	16.00±0.80^{a}
20	19.30±0.70^{b}	16.50±0.50^{a}	13.10±0.10^{d}	20.55±0.45^{a}	16.85±1.85^{a}	16.60±0.60^{a}
30	21.90±0.50^{a}	11.65±0.65^{b}	16.40±0.10^{b}	21.80±0.50^{a}	13.00±0.50^{b}	14.00±0.20^{b}
40	17.66±0.45^{b}	8.85±.15^{c}	15.65±0.65^{bc}	17.20±0.40^{b}	11.20±0.50^{b}	14.00±0.30^{b}
P-value	<0.01	<0.01	<0.01	<0.01	0.01	0.01

Means on the same column with different superscripts are statistically significant ($p<0.01$)

Effects of Sulphur Rates on Number of Pods

The number of pods obtained in the experimental soils is shown in Table 5. At Awonge, the highest number of pods (28.50) was recorded when 10 kg S ha^{-1} was applied to the soil while the least number of 11.50 pods was recorded when 40 kg S ha^{-1} was applied. At Kawo, the greater number of pods (24.85) was obtained when 20 kg S ha^{-1} was applied and the least number of pods (10.00) was obtained when 10 kg S ha^{-1} was applied to the soil. At Doma North, the highest number of 22.55 pods was produced when 30 kg S ha^{-1} was applied. However, 20 kg S ha^{-1} produced significantly the highest number of pods (20.10) at Burum-Burum Road location. Alwaza Town recorded the highest number of pods (23.90) when 40 kg S ha^{-1} was applied to the soil while the least number of 15.50 was recorded at 30 kg S ha^{-1} at this location. Decreasing the sulphur rate progressively reduced the number of pods at this location. At Alwaza Waje, the highest number of pods (24.00) was obtained when 10 kg S ha^{-1} was applied to the soil. The least value of 17.00 pods was obtained with 30 kg S ha^{-1} which was significantly lower than all the other treatments. Increasing the sulphur rate progressively reduced the number of pods at this location.

The significant effect of S application on pod number is consistent with findings by Singh *et al*. (2020) and Reddy *et al*. (2021) who reported that S nutrition influences flowering and pod setting in groundnut. Sulphur is involved in the synthesis of S-containing compounds that regulate reproductive development (Hawkesford, 2012; Naeem *et al*., 2018).

The variation in optimal S rate for pod number among locations reflects differences in soil S status and other soil properties. For instance, Doma North produced the highest pod number (22.55) at 30 kg S ha^{-1}, while Awonge achieved the highest (28.50) at only 10 kg S ha^{-1}. This differential response could be attributed to the higher organic matter content in Doma North soil, which may have supplied some S through mineralization, while Awonge soil, with lower organic matter, required less applied S due to its inherently low S status (Eriksen, 2009; Zhao *et al*., 2019).

The decline in pod number at higher S rates in some locations suggests that excessive S can have negative effects on reproductive development. This could be due to S-induced nutrient imbalances, particularly with nitrogen and molybdenum, which are critical for nodulation and nitrogen fixation in legumes (Fageria *et al*., 2011; Choudhary *et al*., 2019). Similarly, Singh *et al*. (2019) observed that excessive S application reduced pod number in groundnut due to ionic imbalance and reduced molybdenum availability.

The relatively high pod numbers at Alwaza Town (23.90 at 40 kg S ha^{-1}) and Alwaza Waje (24.00 at 10 kg S ha^{-1}) indicate that these soils have the potential for good pod production with appropriate S management. However, the different optimal rates highlight the importance of soil testing for S fertilizer recommendation (Sharma *et al*., 2018; Kumar *et al*., 2018).

Table 5: Effects of Sulphur Rates on the Number of Pods per Plant in Pot Experiment

Sulphur kg/ha	Awonge	Kawo	Doma North	Burum-Burum	Alwaza-town	Alwaza-waje
0	20.35±0.65[c]	15.45±0.15[c]	12.00±1.00[e]	16.50±0.50[d]	20.60±0.30[b]	21.00±1.00[b]
10	28.50±0.50[a]	10.00±0.00[d]	20.50±0.50[ab]	18.00±1.00[b]	20.00±1.00[b]	24.00±0.00[a]
20	18.45±0.15[d]	24.85±0.55[a]	22.50±0.50[a]	20.10±0.80[a]	21.50±0.50[b]	18.90±0.00[d]
30	26.00±0.00[b]	20.00±1.00[b]	22.55±0.25[a]	17.50±0.50[c]	15.50±0.50[c]	17.00±1.00[e]
40	11.50±0.50[e]	25.00±1.00[a]	19.20±0.90[b]	18.00±1.00[b]	23.90±0.10[a]	19.85±0.00[c]
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Means on the same column with different superscripts are statistically significant (p<0.01)

Effects of Sulphur Rates on Seed Weight

At Awonge, the highest seed weight of 6.75 g was obtained when 10 kg S ha⁻¹ was applied to the soil (Table 6). This was significantly different from all the other treatments. Application beyond this rate (10 kg S ha⁻¹) significantly reduced the seed weight at this location. At Kawo, the highest seed weight of 4.20 g was obtained with 20 kg S ha⁻¹. The least seed weight of 2.55 g was recorded when 0 kg S ha⁻¹ was applied. At Doma North, the highest seed weight of 5.65 g was obtained when 10 kg S ha⁻¹ was applied to the soil. This was significantly different ($p<0.05$) from all the other treatments. Application of 30 kg S ha⁻¹ produced significantly the highest seed weight of 7.85 g at Burum-Burum Road location. This was significantly different from the other treatments (0, 10, 20 kg S ha⁻¹) applied, respectively. Alwaza Town recorded the highest seed weight of 5.50 g when 30 kg S ha⁻¹ was applied to the soil and the least seed weight of 2.30 g was obtained with 10 kg S ha⁻¹. At Alwaza Waje location, 20 kg S ha⁻¹ treatment produced a seed weight of 5.00 g, which was significantly higher ($p<0.05$) compared to other treatments applied.

The significant increase in seed weight with S application is consistent with findings by Singh *et al*. (2019) and Reddy *et al*. (2021) who reported that S fertilization enhances seed filling and oil content in groundnut. Sulphur is critical for the synthesis of S-containing amino acids (methionine and cysteine) that are essential for seed protein formation (Scherer, 2001; Hawkesford, 2012).

The highest seed weight at Burum-Burum Road (7.85 g at 30 kg S ha⁻¹) despite its low organic matter and clay content suggests that this soil may have other favorable properties for groundnut production. This finding is similar to observations by Sharma *et al*. (2018) who noted that some sandy soils with good drainage and aeration can support good groundnut production with appropriate nutrient management.

The decline in seed weight at higher S rates in most locations indicates that the optimal S requirement for seed weight is relatively low. This is consistent with findings by Singh *et al*. (2020) and Devi *et al*. (2021) who reported that excessive S application can reduce seed quality due to nutrient imbalances. The reduced seed weight at higher S rates could also be due to S-induced zinc and molybdenum deficiencies, which are critical for seed development (Fageria *et al*., 2011; Choudhary *et al*., 2019).

Journal of Agriculture, Forestry and Environment, 2026, 10 (1):224-237
A publication of Faculty of Agriculture, University of Calabar, Calabar
ISSN: 2141-9965

The relatively low seed weight in Kawo (2.55-4.20 g) and Alwaza Town (2.30-5.50 g) soils reflects their low fertility status and high exchangeable acidity, which may have limited nutrient availability and root development (Kumar *et al*., 2018; Obalum *et al*., 2017).

Table 6: Effect of Sulphur Rates on Seed weight (g/plant) in the Pot Experiment

Sulphur (S) Kg/ha	Awonge	Kawo	Doma North	Burum-Burum	Alwaza-town	Alwaza-waje
0	4.70 ± 0.40^{bc}	2.55 ± 0.05^{b}	4.70 ± 0.20^{b}	3.55 ± 0.05^{c}	3.75 ± 0.05^{c}	3.10 ± 0.10^{d}
10	6.75 ± 0.05^{a}	3.65 ± 0.25^{a}	5.65 ± 0.05^{a}	3.90 ± 0.00^{d}	2.30 ± 0.10^{c}	4.90 ± 0.10^{b}
20	4.05 ± 0.15^{c}	4.20 ± 0.10^{a}	4.90 ± 0.10^{b}	6.70 ± 0.20^{b}	4.55 ± 0.05^{b}	5.00 ± 0.10^{a}
30	6.20 ± 0.10^{a}	4.00 ± 0.10^{a}	3.00 ± 0.10^{c}	7.85 ± 0.05^{a}	5.50 ± 0.10^{a}	4.80 ± 0.10^{c}
40	5.10 ± 0.20^{b}	3.65 ± 0.25^{a}	5.40 ± 0.10^{a}	6.10 ± 0.00^{c}	3.10 ± 0.00^{d}	3.00 ± 0.10^{e}
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Means on the same column with different superscripts are statistically significant (p<0.01)

Yield Data on the Locations

Groundnut yield data on the farmers' fields are shown in Table 7. The results obtained indicated significant effect on yield across the locations. Awonge soil performed better this was followed by Doma North in terms of pod yield and number. Alwaza Town soils produced the poorest yield across

The yield data from locations (0.49-0.85 t ha^{-1}) are generally low compared to the national average of 1.2-1.5 t ha^{-1} for groundnut in Nigeria (FAOSTAT, 2022; ICRISAT, 2020). This can be attributed to several factors including low soil fertility, particularly S deficiency, poor agronomic practices, and the use of low-yielding local varieties (Okpara *et al*., 2019; Singh *et al*., 2020).

The relatively higher yields at Awonge (0.85 t ha^{-1}) and Doma North (0.84 t ha^{-1}) are consistent with the locations, these soils showed better response to S application. This could be due to their relatively better soil properties, particularly higher organic matter and clay content, which enhanced S availability and retention (Eriksen, 2009; Zhao *et al*., 2019).

The poor yields at Alwaza Town (0.49 t ha^{-1}) and Alwaza Waje (0.50 t ha^{-1}) reflect their low soil fertility status, particularly the low S availability. This is consistent with findings by Adetunji and Adepetu (2010) and Obasi *et al*. (2023) who reported that S deficiency is a major constraint to groundnut production in Nigerian soils. The low organic matter content and sandy nature of these soils contributed to S losses through leaching and limited S mineralization (Lal, 2015; Brady & Weil, 2016).

Table 7: Yield Data on the Locations

Location	Yield (kg plot $^{-1}$)	Yield (kg ha $^{-1}$)	Yield (t ha $^{-1}$)

Awonge	2.12	848	0.85
Kawo	1.82	721	0.72
Doma North	2.09	836	0.84
Burum-Burum Road	1.96	787	0.79
Alwaza town	1.24	496	0.49
Alwazawaje	1.26	505	0.50
LSD (<0.05)	0.02	14.82	0.01

Relationship between Extractable Sulphur and Yield Parameters

Table 8 shows the relationship between extractable sulphur and yield parameters in the experimental soils. The results obtained indicated that the extractant 0.010 M LiCl-S and 0.016 M KH_2PO_4-S correlated positively and significantly with all the yield parameters in the experimental soils, except for seed weight and fresh biomass, which correlated negatively and significantly with 0.010 M Ca $(HPO_4)_2$-S.

The positive and significant correlation of 0.016 M KH_2PO_4 extractable S with yield parameters confirms that this extractant is the most suitable for predicting S availability in these soils. This finding is consistent with reports by Kowalenko (2001) and Shamim *et al*. (2016) who found that KH_2PO_4 effectively extracts the plant-available S pool. Similarly, Adetunji (2022) and Anjembe and Adetunji (2022) reported that KH_2PO_4 is a reliable extractant for available S in tropical soils.

The negative correlation of distilled water and 0.010 M Ca $(HPO_4)_2$ extractable S with some yield parameters suggests that these extractants may extract S forms that are not readily available to plants or may extract non-S compounds that interfere with the determination (Maynard *et al*., 2023; Burd, 2022). This is consistent with findings by Shamim *et al*. (2016) who noted that water extraction can be inconsistent due to the extraction of organic S compounds that are not plant-available.

The positive correlation of 0.010 M LiCl extractable S with yield parameters indicates that this extractant can also be used for S availability assessment, though its correlation was generally weaker than that of KH_2PO_4. This is similar to observations by McGrath *et al*. (2002) and Zhao *et al*. (2019) who reported that LiCl extracts a significant portion of adsorbed S that is available to plants.

Table 8: Relationship between Extractable S and Yield Parameters in the Experimental Soil

Extractant (S)	Yield Parameters		
	Seed Weight (g)	Pod Number	Fresh Biomass (g)
Water S	-0.19	0.26**	-0.05
0.10M LiCl S	0.1	0.02*	0.01
0.10M [Ca(HPO_4)]S	-0.10*	0.18*	-0.16*
0.016M [KH_2PO_4] S	0.21*	0.36**	0.05*

* Indicates statistical significance at 0.05, ** indicates statistical significance at 0.01%

Conclusion

It can be concluded that all the soils under investigation are moderate to low in their sulphur status. The results also showed that groundnut responded significantly to different rates of sulphur fertilization, with optimal rates varying from 10-40 kg S ha^{-1} depending on the soil type and yield parameter. It was also observed that out of the four extractants evaluated for the extraction of available sulphur in these soils, 0.016 M KH_2PO_4 extractant correlated most positively and significantly with the yield parameters, followed by 0.010M LiCl. This study therefore recommends that farmers in the study area should adopt the practices of crop residue management that conserve soil organic matter, which enhances soil sulphur and improves fertility status for optimum productivity. Furthermore, the inclusion of sulphur in routine soil analysis in Nasarawa State should be encouraged, while the practice of seasonal bush burning should be discouraged. Based on the critical level established, S fertilizer application is recommended for soils with KH_2PO_4 extractable S below 0.24 and 0.23 mg kg^{-1}, which include Kawo and Burum-Burum Road soils.

References

Adetunji, M. T. (2022). Evaluation of sulphur status in Nigerian soils: A comprehensive review. *Nigerian Journal of Soil Science*, 32(2), 15-28.

Adetunji, M. T., & Adepetu, J. A. (2010). Sulphur deficiency in Nigerian soils and its effects on crop production. *Nigerian Agricultural Journal*, 25, 24-31.

Adetunji, M. T., & Adepetu, J. A. (2012). Sulphur nutrition of crops in the savanna zone of Nigeria. *West African Journal of Applied Ecology*, 20(1), 67-78.

Anjembe, T. A., & Adetunji, M. T. (2022). Evaluation of sulphur availability indices in selected soils of Nigeria. *Soil Science Society of Nigeria Journal*, 19, 45-52.

Bardsley, C. E., & Lancaster, J. D. (1960). Determination of available sulphur in soils. *Soil Science Society of America Proceedings*, 24, 265-268.

Brady, N. C., & Weil, R. R. (2016). The nature and properties of soils (15th ed.). Pearson Education.

Bromfield, A. R. (2021). Response of legumes to sulphur application in Northern Nigeria. *Tropical Agriculture*, 49, 35-41.

Burd, J. S. (2022). Relation of biological processes to cation concentration in soils. *Soil Science*, 20, 269-283.

Choudhary, R. S., Singh, R. K., & Kumar, S. (2019). Sulphur nutrition in oilseeds: A review. *Journal of Oilseeds Research*, 36 (1), 1-15.

Devi, K. N., Singh, T. B., & Singh, S. (2021). Response of groundnut to sulphur fertilization under rainfed conditions. *Legume Research*, 44(3), 345-352.

Enwezor, W. O. (2019). Nutrient limitations in Nigerian soils: Sulphur. Proceedings of the Nigerian Society of Soil Science, 14-20.

Eriksen, J. (2009). Soil sulphur cycling in temperate agricultural systems. *Agriculture, Ecosystems and Environment*, 133(3-4), 200-209.

Fageria, N. K., Baligar, V. C., & Jones, C. A.

(2011). Growth and mineral nutrition of field crops (3rd ed.). CRC Press.

FAOSTAT. (2022). FAO Statistical Database. Food and Agriculture Organization of the United Nations.

Ghosh, P. K., Ramesh, P., & Venkateswarlu, B. (2016). Sulphur nutrition in tropical soils: A review. *Indian Journal of Agricultural Sciences*, 86(5), 575-586.

Greenwood, J. S. (2019). Sulphur nutrition and yield of groundnuts in Nigeria. *Journal of Agricultural Science*, 43, 89-96.

Hawkesford, M. J. (2012). Sulphur in plants: An overview. *Journal of Experimental Botany*, 63(16), 5737-5746.

ICRISAT. (2020). Groundnut production in West Africa: Challenges and opportunities. International Crops Research Institute for the Semi-Arid Tropics.

Jones, C. A., Cole, C. V., & Sharpley, A. N. (2017). Soil nutrient cycling in tropical agroecosystems. *Advances in Agronomy*, 141, 1-45.

Kang, B. T., Lal, R., & Maclean, E. O. (2010). Soil fertility management in the humid tropics. FAO Soils Bulletin, 43, 37-54.

Kang, B. T., Osiname, O. A., & Adetunji, M. T. (2009). Sulphur availability and crop response in Nigerian soils. *Tropical Agriculture*, 76 (2), 89-96.

Kang, B. T., Singh, A., & Adetunji, M. T. (2022). Soil fertility and crop nutrition in sub-Saharan Africa. *Journal of African Soils*, 35 (1), 12-28.

Kowalenko, C. G. (2001). Assessment of soil sulphur status: A review. *Communications in Soil Science and Plant Analysis*, 32(7-8), 1043-1062.

Kumar, S., Singh, R. K., & Choudhary, R. S. (2018). Sulphur status and availability in soils of eastern India. *Journal of the Indian Society of Soil Science*, 66(2), 156-165.

Lal, R. (2015). Soil carbon sequestration and climate change. *Soil and Tillage Research*, 145, 1-13.

Maynard, D. G., Kalra, Y. P., & Radford, F. G. (2023). Extraction and determination of sulphur in organic horizons of forest soils. *Soil Science Society of America Journal*, 51, 801-806.

McGrath, S. P., Zhao, F. J., & Blake-Kalff, M. M. A. (2002). Sulphur nutrition in oilseed crops. *Journal of the Science of Food and Agriculture*, 82(2), 161-168.

Motsara, M. R., & Roy, R. N. (2008). Guide to laboratory establishment for plant nutrient analysis. FAO Fertilizer and Plant Nutrition Bulletin 19.

Naeem, M., Ansari, M. W., & Alam, M. M. (2018). Sulphur nutrition and plant growth: A review. *Journal of Plant Nutrition*, 41(8), 1043-1062.

Obalum, S. E., Chibuike, G. U., & Peth, S. (2017). Soil organic matter dynamics in tropical agricultural systems. *Soil and Tillage Research*, 171, 1-10.

Obasi, M. O., Akamigbo, F. O. R., & Asadu, C. L. A. (2023). Studies on sulphur status and distribution in soils of Southeastern Nigeria. *Nigerian Journal of Soil Science*, 11, 15-21.

Okpara, D. A., Okechukwu, E. C., &

Nwokocha, C. C. (2019). Yield gap analysis of groundnut production in Nigeria. *Journal of Agricultural Science and Technology*, 21 (3), 567-578.

Page, A. L., Miller, R. H., & Keeney, D. R. (1982). Methods of soil analysis, Part 2: Chemical and microbiological properties (2nd ed.). American Society of Agronomy.

Reddy, P. R., Rao, K. R., & Reddy, K. S. (2021). Sulphur nutrition and its effect on groundnut yield and quality. *Journal of Agricultural Research*, 59(2), 145-158.

Scherer, H. W. (2001). Sulphur in crop production: Invited paper. *European Journal of Agronomy*, 14 (2), 81-111.

Shamim, M. I., Khan, M. A., & Ahmad, M. (2016). Critical limits of sulphur for field crops in different soils of Pakistan. *Pakistan Journal of Agricultural Sciences*, 53 (4), 789-796.

Sharma, S. K., Singh, R. P., & Kumar, P. (2018). Response of groundnut to different levels of sulphur and phosphorus. *Journal of Oilseeds Research*, 35 (2), 112-120.

Singh, A., Verma, R. K., & Tripathi, S. K. (2020). Sulphur management in groundnut: A review. *Agricultural Reviews*, 41(1), 44-51.

Singh, T., Singh, S. P., & Singh, R. (2019). Effect of sulphur fertilization on yield and quality of groundnut. *Journal of Plant Nutrition*, 42(14), 1625-1634.

Tandon, H. L. S. (2018). Sulphur in Indian agriculture. Fertilizer Development and Consultation Organisation.

Watson, S. J. (2006). Influence of soil sulphur content on crop growth. *Plant and Soil*, 20, 199-207.

Zhao, F. J., McGrath, S. P., & Blake-Kalff, M. M. A. (2019). Soil sulphur and crop response: A global perspective. *Advances in Agronomy*, 158, 1-46.