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Synergism of sulfur availability and agronomic nitrogen use efficiency

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Abstract

Nutrient management strategies that exploit nutrient elements' synergistic interaction to enhance nitrogen use efficiency (NUE) are needed for economic and environmental reasons. A field study was carried out during the 2020–2022 growing seasons at six locations in three countries: two each in the United States, Ghana, and Mali using three sulfur (S) sources with different bioavailability levels (micronized elemental S, untreated elemental S, and ammonium sulfate); applied at five S application rates: site-specific recommended S rate (SR), 25%, 50%, 75%, and 125% of SR; and a single nitrogen (N) application rate (site-specific recommended N rate) to comprehensively investigate the influence of S availability on NUE. Specific objectives were to evaluate the impact of S availability on corn (*Zea mays* L.) yield, N uptake, and NUE. Regardless of the S source and experimental site, the aboveground S and N uptake were strongly and positively correlated ($r > 0.88$). Increases in apparent N recovery efficiency and agronomic NUE occurred with corresponding increases in S application rate, irrespective of the site and S source. The combined data showed that the agronomic efficiency of applied N fertilizer sources could be enhanced significantly by increasing S availability in soils. With the rising N fertilizer costs in recent times, N losses from the applied fertilizer are a drain on farmers' income and of environmental concern. Thus, increasing NUE is a needed strategy to safeguard against excessive N application, increase farm profits, and minimize N losses to the environment that could disrupt the ecosystem function.

1 | INTRODUCTION

The importance of nitrogen (N) fertilization cannot be overemphasized because its deficiency significantly reduces crop yield. Several studies have shown that N is a critical element for photosynthesis and thus greatly affects radiation use efficiency, which ultimately drives the overall increased crop productivity (Prasad & Hobbs, 2018). Studies have shown that N is involved in many crucial physiological processes, including the formation of chlorophyll, amino acids, protein synthesis, and plant hormones enhancement, among others, resulting in enhanced yield and crop quality

Abbreviations: AEZ, agroecological zone; ANUE, agronomic nitrogen use efficiency; AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur; NUE, nitrogen use efficiency; SR, recommended sulfur application rate.

(Anas et al., 2020). Nevertheless, the excessive use of N has severe environmental consequences including soil acidification, pollution of surface water leading to the eutrophication of freshwater resources, groundwater contamination, and increases in the emission of greenhouse gasses (Mohanty et al., 2020; Tiong et al., 2021). Therefore, it is critical to implement good strategies for managing N, which could enhance the efficiency of N use and thus minimize N losses to the environment without sacrificing yield and crop quality.

Achieving high N use efficiency (NUE) will result in significant benefits, both environmental and economical, and sustainable production systems (Fixen et al., 2015; Gastal et al., 2015). Several studies have reported that many factors influence NUE, including adequate water supply (Timilsena et al., 2015), improved tillage practices (Habbib et al., 2016), improved germplasm (Ciampitti & Vyn, 2012), and adequate supply of other essential plant nutrients, including sulfur (S) (Duncan et al., 2018). Fageria (2014) reported that nutrient interaction is among the critical factors that influence NUE in many field crops. Studies have shown that nutrient interactions can be either synergistic (positive interaction), antagonistic (negative) or even absent (zero interaction) (Rietra et al., 2017). Therefore, taking advantage of the synergistic interactions could result in enhanced NUE, yield, and crop quality. In field and greenhouse studies, Shivay et al. (2016) and Byatvarkeshi and Zareabbyaneh (2016) observed that the inclusion of S in the N fertilization program increased N recovery efficiency and NUE by 50% and 60%, respectively, in wheat crops. In a 3-year study, Carciochi et al. (2020) showed a positive interaction between S and N resulting in increased corn (*Zea mays* L.) yield by more than fourfold, compared to the application of N alone. In another study, McGrath and Zhao (2009) showed that in S-deficient soils, the yield, NUE, oil, and protein contents of rapeseed (*Brassica napus*) decreased significantly, and when in the absence of other limiting essential nutrients, the application of N was increased from 180 to 230 kg ha^{-1}.

Studies have shown that S and N possess similar assimilation pathways and are key constituents of several physiological processes in plants, including the photosynthetic process, and electron transport chain (Abadie & Tcherkez, 2019; Gigolashvili & Kopriva, 2014). Abadie and Tcherkez (2019) and Hooghe et al. (2013) observed that the photosynthetic efficiency was greatly reduced when S was deficient in the soil and attributed it to inefficient chlorophyll production in the absence or limited supply of S. From previous research studies, Hooghe et al. (2013) and Gigolashvili and Kopriva (2014) reported that S-containing proteins are crucial for photosynthesis and carbon metabolism and ultimately lead to the synthesis of photo-assimilates, which have the possibility of increasing NUE. Therefore, we hypothesized that the availability of S could enhance the absorption and utilization of N in plants.

Core Ideas

- Nitrogen (N) losses from applied fertilizer are both a great economic drain and a major environmental concern.
- Exploiting the synergistic interaction of nutrient elements is needed to improve N use efficiency (NUE).
- Sulfur (S) and N uptake were strongly and positively correlated ($r > 0.88$).
- Increase in apparent N recovery efficiency and agronomic NUE occurred with an increasing S application rate.
- Increasing NUE is expected to increase returns on investment and safeguard against ecosystem degradation.

Most of the previous studies that assessed the interactions among nutrients were conducted under optimal soil and environmental conditions that eliminated external confounding effects such as water stress, fluctuations in day and night temperature, unfavorable soil pH, and inadequate supply of other essential plant nutrients. Only a few studies have used the agronomic approach, which does not control for external influences, to study nutrient interactions. Although the latter approach has the disadvantage that the uncontrolled external influences could limit the validity and applicability of the results to the prevailing conditions only due to varying environmental variables, it remains the most powerful result since the study is carried out in naturally occurring environmental conditions encountered by farmers. Therefore, in this study, the agronomic approach was used to determine the synergism of S availability and NUE. In addition, studies that have evaluated the N and S interaction in soils have relied on only one S fertilizer product including gypsum ($CaSO_4$ $2H_2O$, 18% S) (Carciochi et al., 2020) or ammonium sulfate ($[NH_4]_2SO_4$, 24% S) (Agyin-Birikorang et al., 2022, 2023) as the S source(s) in their studies. However, several studies have shown that S fertilizer sources have different bioavailability levels, with some sources having rapidly soluble (e.g., ammonium sulfate), controlled-released (e.g., micronized elemental sulfur), and rarely-soluble (e.g., elemental sulfur) properties (Boubakary et al., 2023). Therefore, to comprehensively elucidate the positive influence of S availability on NUE, S sources with varying bioavailability levels were used in this study, with an overall objective of ascertaining the synergistic effect of S availability on NUE. Specific objectives were to assess S application rates and adequate N supply on corn yield, S and N uptake and recovery efficiencies, and NUE as influenced by S availability.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

Field studies were conducted during the 2020–2022 growing seasons at six locations in three countries: two each in the United States, Ghana, and Mali. In the United States, one experiment was sited at a private farm in east Memphis, TN (35˚08′03.0″ N 89˚58′16.0″ W) and the other at Barton, AL (34˚44′ 35.2″ N, 87˚54′ 02.4″ W). The soil at the Memphis site is an Alfisol classified as Morganfield silt loam (fine-silty, mixed, active, thermic Typic Hapludalfs), and that at the Barton, AL site is a weathered Ultisol, classified as fine, kaolinitic, thermic Rhodic Paleudults (Soil Survey Staff, 2009). The trials in Ghana were established in Karaga (9˚55′ 24.5″ N, 0˚25′ 32.6″ W) and Gushegu (9˚43′ 09.3″ N, 0˚19′ 12.7″ W), both located in the Guinea Savanna agroecological zone (AEZ). The soil at the Karaga site is classified as a Luvisols and that at the Gushiegu site as a Plinthosols (ISSS/ISRIC/FAO, 1998). The trials in Mali were established in Sikasso (11˚19′ 02.1″ N, 5˚40′ 03.1″ W) located in the Southern Sudan Savanna AEZ, and Kayes (14˚27′ 46.2″ N, 11˚26′ 44. 3″ W) located in the Sahel AEZ (Akinseye et al., 2016). The soil at both sites is classified as Ferric Lixisols (ISSS/ISRIC/FAO, 1998). To characterize the native soil physicochemical properties, soil samples were collected from each plot prior to the start of the study. Thus, each site was partitioned into 24 subunits, and from each of them, composite surface soil samples (i.e., combining twenty 2.5-cm diameter core samples) were obtained from 0 to 15 cm deep (Table 1). Total rainfall and daily temperature changes during the entire duration of the study were recorded with a weather station established at each experimental site. The number of wet days, total precipitation, and the minimum and maximum temperatures measured at each of the experimental sites for the three growing seasons are provided in Table 2.

2.2 | Treatments, field layout, and experimental setup

The trials consisted of three S sources (micronized elemental sulfur [MES; 14.5% S, 32% N], untreated elemental sulfur [ES; 92% S], and ammonium sulfate (AS; 24% S, 21% N]); five S application rates ((i) the site-specific recommended S application rate [SR], (ii) one-fourth of the recommended S rate [25% SR], (iii) half of the recommended S rate [50% SR], (iv) three-fourth of the recommended S rate [75% SR], and (v) 1¼ of the recommended S rate [125% SR]); and a single N application rate (the site-specific recommended N application rate). Thus, in the USA sites, S was applied at 25, 6.25, 12.5, 18.75, and 31.25 kg S ha^{-1}, respectively; in the Ghana sites, S was applied at 30, 7.5, 15, 22.5, and 37.5 kg S ha^{-1}, respectively; in the Mali sites, S was applied at 50, 12.5, 25, 37.5, and 62.5 kg S ha^{-1} respectively. The N application rates for the United States, Ghana, and Mali sites were 300, 200, and 180 kg N ha^{-1}, respectively. The treatments included a control that did not contain S. The treatments were organized in a split-plot randomized complete block design, with the S sources occupying the main plots and the S application rates occupying the subplots, and a blanket N application to all blocks. Each treatment was replicated four times at each site, resulting in a total of 64 plots per site [((3 S sources × 5 application rates) + (control)) × 4 blocks].

Based on fertilizer recommendations for each site, the other essential nutrients that were limiting, including phosphorus (P), potassium (K), and zinc (Z), were applied in sufficient quantities, such that S remained the only limiting nutrient. P was applied as triple super phosphate (45% P_2O_5), K as muriate of potash (62% K_2O), and Zn as zinc chloride (50% Zn). Nitrogen was applied mainly as urea, but since the AS and MES contained N (21% and 32% N, respectively), adequate quantities were applied to supply all the required S as determined for each treatment, and the deficit in N was made up with urea (46% N).

2.3 | Planting of corn

At each experimental site, the corn hybrid and the recommended planting spacing most commonly used by producers was used as the test corn hybrid. Thus, in the United States, a corn hybrid, Dekalb 6483 (YieldGardVT Triple), was planted at the two sites during the period of the study at a spacing of 76.2 cm × 16.5 cm, resulting in a seeding rate of 79,500 ha^{-1}. At the two sites in Ghana, a drought-tolerant, medium-maturing (115 days) corn hybrid (*Pan 53*) was planted at a spacing of 80 cm × 20 cm, resulting in a seeding rate of 62,500 ha^{-1}. In Mali, an early-maturing (90 days) drought-tolerant hybrid (*Sanu* [TZEI 86 × TZEI 60]) was planted at the Sikasso site, and at the Kayes site, an early-maturing (90 days), Striga-tolerant corn hybrid (*Mata* [TZE-Y Pop DT STRC4 × TZEI 13]) was planted. Both corn hybrids used in the trials in Mali were planted at a spacing of 75 cm × 25 cm, resulting in a plant population of 66,670 plants ha^{-1}.

2.4 | Measurements, data collection, and calculations

At the silking (R1) growth stage, 10 randomly selected plants were manually harvested from rows immediately outside the four middle rows, and subsamples were weighed and oven-dried at 65˚C (till weights stabilized) to determine biomass dry weights. At maturity (R6), the four middle rows of each

TABLE 1 Selected soil physicochemical properties of the experimental sites.

Characteristics	Ghana		United States		Mali	
	Karaga	Gushiegu	Barton, AL	Memphis, TN	Sikasso	Kayes
pH-H_2O	6.84 ± 0.11	6.52 ± 0.20	6.30 ± 0.24	6.44 ± 0.36	6.48 ± 0.21	6.15 ± 0.22
Sand (g kg^{-1})	480	450	310	280	560	680
Silt (g kg^{-1})	350	360	500	510	260	80
Clay (g kg^{-1})	170	190	190	210	180	240
Organic C (g kg^{-1})	3.45 ± 0.38	3.79 ± 0.41	7.34 ± 1.02	6.48 ± 0.29	3.26 ± 0.24	3.62 ± 0.39
Nitrate-N (mg kg^{-1})	3.38 ± 0.42	2.15 ± 0.31	5.15 ± 0.48	3.14 ± 0.48	2.14 ± 0.18	1.92 ± 0.12
Ammonium-N (mg kg^{-1})	8.44 ± 0.92	5.50 ± 0.62	4.10 ± 0.47	4.18 ± 0.18	3.05 ± 0.19	2.46 ± 0.25
Available P (Pi-P) (mg kg^{-1})	4.28 ± 0.44	2.88 ± 0.21	8.00 ± 0.96	6.82 ± 0.34	5.13 ± 0.66	4.17 ± 0.45
Sulfate-S (mg kg^{-1})	2.03 ± 0.11	1.12 ± 0.17	2.21 ± 0.62	2.78 ± 0.21	1.96 ± 0.12	1.32 ± 0.09
Zinc (mg kg^{-1})	0.24 ± 0.04	0.63 ± 0.04	0.21 ± 0.02	0.19 ± 0.17	0.46 ± 0.03	0.32 ± 0.02
Boron (mg kg^{-1})	0.37 ± 0.02	0.43 ± 0.04	0.32 ± 0.04	0.36 ± 0.22	0.29 ± 0.02	0.38 ± 0.04
Exchangeable K (cmol kg^{-1})	0.14 ± 0.01	0.2 ± 0.01	0.36 ± 0.44	0.39 ± 0.41	0.16 ± 0.01	0.21 ± 0.02
Exchangeable Ca (cmol kg^{-1})	1.31 ± 0.11	1.43 ± 0.12	3.94 ± 0.53	3.71 ± 0.64	2.04 ± 0.19	3.16 ± 0.34
Exchangeable Mg (cmol kg^{-1})	0.75 ± 0.06	0.93 ± 0.12	1.63 ± 0.16	1.76 ± 0.83	0.86 ± 0.09	0.92 ± 0.10
CEC (cmol kg^{-1})	3.14 ± 0.31	2.18 ± 0.12	5.19 ± 1.27	5.93 ± 0.66	1.68 ± 0.14	1.92 ± 0.12

Note: Numbers are mean values of 24 replicates ± standard error.
Abbreviation: CEC, cation exchange capacity.

TABLE 2 Measured total precipitation and temperature range at the experimental sites during the study period (2020–2022) growing seasons.

Location	No. of wet days			Total precipitation (mm)			Temperature range (˚C) Minimum			Temperature range (˚C) Maximum		
	2020	2021	2022	2020	2021	2022	2020	2021	2022	2020	2021	2022
Barton, AL	53	51	49	1240	1208	1175	14.5	12.4	14.7	37.2	38.4	38.8
Memphis, TN	53	56	58	1299	1309	1368	12.6	13.4	13.7	30.2	33.9	32.6
Gushiegu	54	52	50	1036	1104	1072	17.3	17.6	18.4	41.6	43.1	42.0
Karaga	49	47	48	912	986	942	19.1	17.8	17.5	43.6	43.1	44.4
Sikasso	41	43	40	864	873	889	19.8	19.2	21.4	46.5	46.1	48.2
Kayes	38	35	36	687	709	765	19.8	18.9	18.6	46.2	47.5	46.8

plot were harvested. The moisture content of the grain yields was adjusted to 15.5% to ensure uniform treatment comparison, following the procedure of Agyin-Birikorang et al. (2020). The harvested samples were separated into stover and grain components and analyzed individually to determine tissue N and S contents of each component following the procedures of Gallaher et al. (1975) and Kovar (2021), respectively. The N and S uptake was estimated as the product of the total biomass (grain + stover) and the tissue N and S contents, respectively. Apparent N and S recovery efficiency was estimated with a modification of the method described in Agyin-Birikorang et al. (2020):

$$\mathrm{RE}\ (\%) = \frac{(U_f - U_0)}{Q} \times 100, \quad (1)$$

where RE is the apparent N or S recovery efficiency, U_f is either aboveground N or S uptake as a response of S supply (kg ha^{-1}), U_0 is either aboveground N or S uptake from the control (no S) (kg ha^{-1}), and Q is the quantity of either N or S applied (kg ha^{-1}).

Agronomic N use efficiency (ANUE) as influenced by S application was calculated following the procedure described in Carciochi et al. (2020):

$$\mathrm{ANUE} = \frac{(Y_1 - Y_0)}{Q_N}, \quad (2)$$

where Y_1 is the grain yield as a response of S supply, Y_0 is the grain yield from the control (no S), and Q_N is the quantity of N applied.

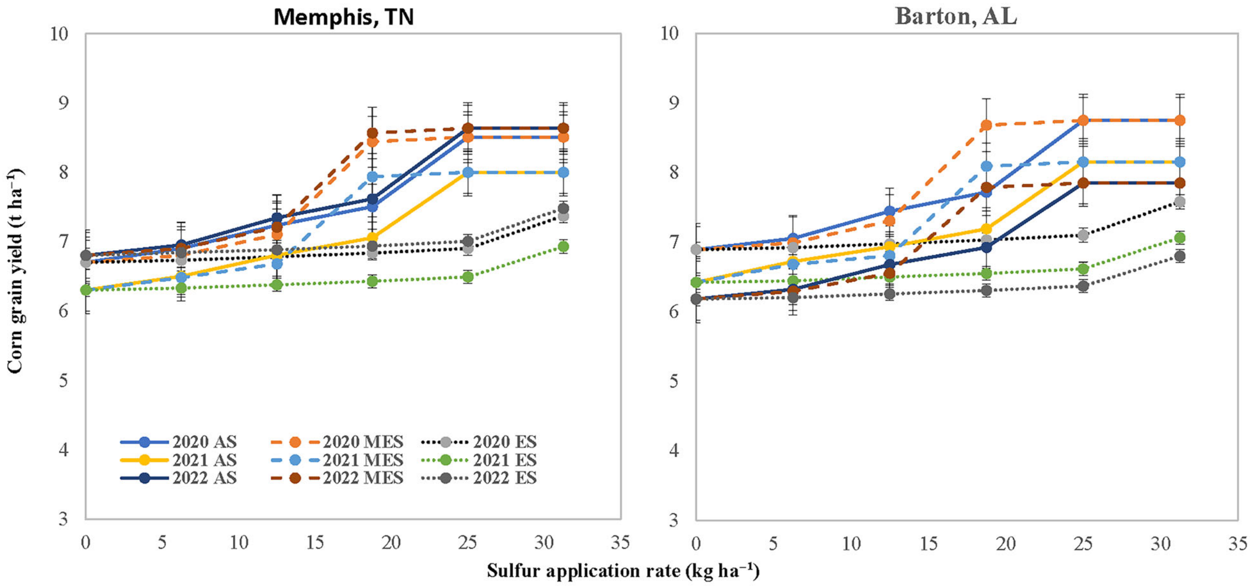

FIGURE 1 Corn grain yield from the Barton, AL, and Memphis, TN (USA) sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. AS, ammonium sulfate, ES, elemental sulfur; MES, micronized elemental sulfur.

2.5 | Statistical analyses

Using the analysis of variance mixed model procedure, the initial analysis revealed a highly significant ($p < 0.01$) variation among the experimental sites and the growing seasons. Therefore, each experimental site and growing season was analyzed separately using the generalized linear mixed model (PROC GLIMMIX, SAS 9.4) season (SAS Institute, 2018) to determine the effects of treatments on yield, N and S uptake, N and S recovery efficiencies, and the post-harvest soil N concentration. In these analyses, replications and their interactions were treated as random effects, whereas the treatment was handled as a fixed effect (Littell et al., 1996). Tukey's honest significant difference test was used to separate treatment means, and a probability threshold of less than 0.05 ($p < 0.05$) was considered significant. The correlation analysis to assess the strength of the relation between S and N uptake was conducted with the PROC CORR procedure (SAS 9.4; SAS Institute, 2018).

3 | RESULTS AND DISCUSSION

3.1 | The influence of sulfur and nitrogen availability on corn yield

There was a significant ($p < 0.05$) location variation in corn yield; however, this notwithstanding, the effect of the growing season (year) on corn yield was highly significant ($p < 0.01$) in all six locations. At both locations in the United States (Memphis, TN, and Barton, AL), grain yield was significantly lower in the 2022 growing season than in the 2020 and 2021 growing seasons (Figure 1). Conversely, at the Ghana locations, grain yield observed in the three growing seasons was the highest in the 2021 growing season, followed by the 2022 and 2020 growing seasons, in that order (Figure 2), whereas in the Mali locations, the highest grain yield was observed in the 2022 growing season, followed by that of the 2021 growing season with the lowest yield occurring in the 2020 growing season (Figure 3). Since corn was grown under rainfed conditions at all locations, the significant year effect could be attributed to the yearly rainfall variation (amounts, intensity, and distribution) during the study period (Table 2). Regardless of the year effect on corn yield, the impacts of S availability emanating from the S sources and application rate were manifested in similar trends in yield.

In addition, significant differences among the S sources ($p < 0.05$) and application rate ($p < 0.01$) were observed. For the entire duration of the study, AS and MES were agronomically more effective than ES. At lower application rates <75% SR, grain yield with AS was significantly higher than that of MES. However, at S rates of 75% SR, grain yield with MES was significantly higher than that of AS, but at the recommended S rate (SR) and 125% SR, there were no significant differences between AS and MES sources at all experimental sites. Averaged over the duration of the study, at USA locations, there were no significant differences ($p > 0.05$) between AS and MES in terms of yield, which were significantly greater than that observed with the ES (Figure 1). At the recommended SR, the average grain yield with AS and MES was 8.32 and 8.28 Mg ha^{-1}, respectively, and that of ES was 6.86 Mg ha^{-1}. The low yield with ES is consistent with the finding that ES is virtually inert and rarely water-soluble,

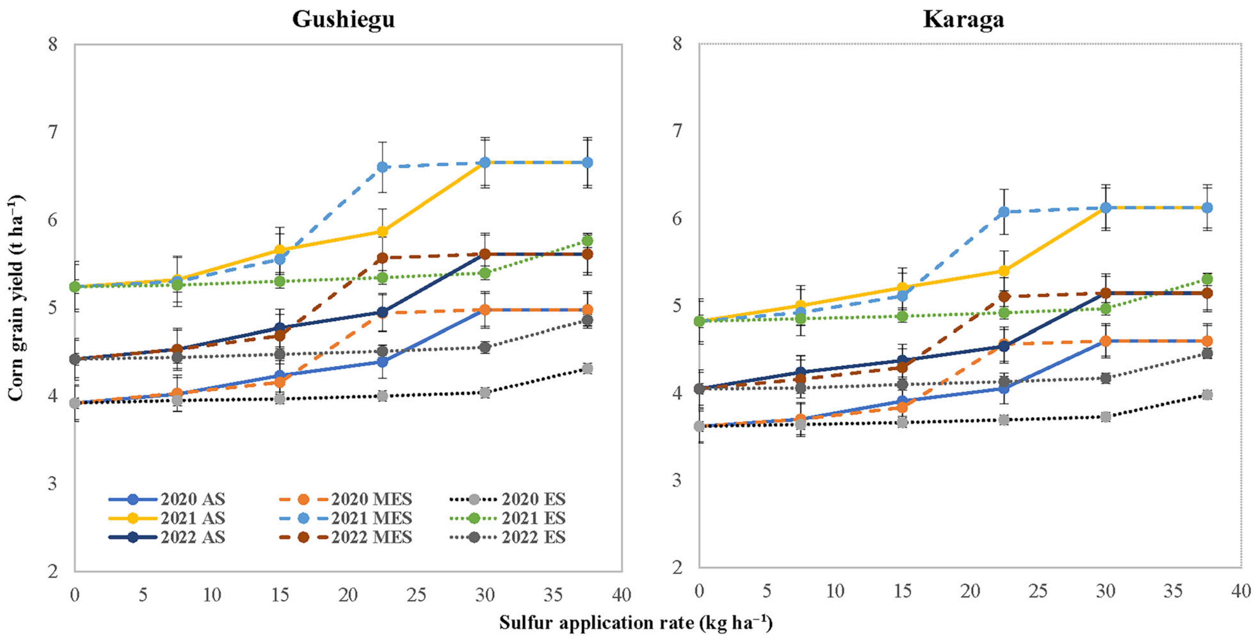

FIGURE 2 Corn grain yield from the Gushiegu and Karaga (Ghana) sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. AS, ammonium sulfate, ES, elemental sulfur; MES, micronized elemental sulfur.

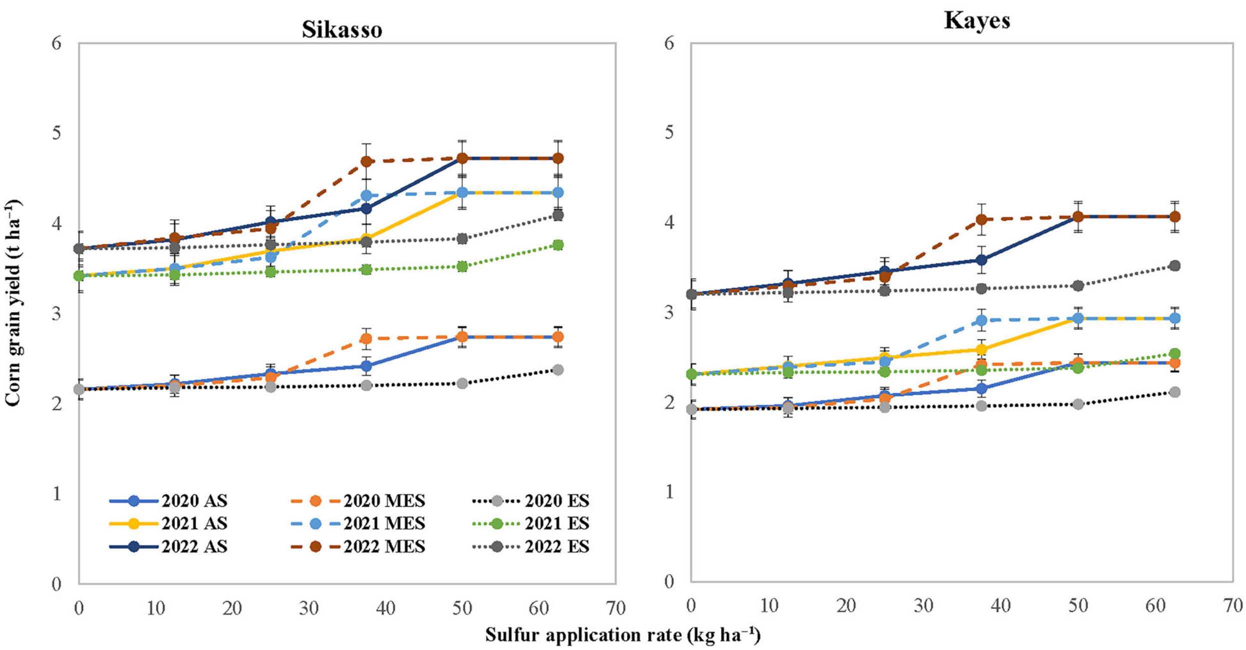

FIGURE 3 Corn grain yield from the Sikasso and Kayes (Mali) sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. AS, ammonium sulfate, ES, elemental sulfur; MES, micronized elemental sulfur.

which requires oxidation to sulfate to become plant-available, but the oxidation process by which ES is converted to sulfate is relatively very slow (Zhao et al., 2015). Therefore, it was not unusual that lower yields occurred with the ES source.

Not surprisingly, with AS, the highest corn yield was observed with 125% SR, which was not significantly different from that of SR, but significantly higher than that of 75% SR, 50% SR, and 25% SR in that order, with the lowest grain yield occurring with the control (no S application) (Figures 1–3).

With MES on the other hand, there were no significant differences in grain yield among the 125% SR, SR, and 75% SR treatments, which were significantly higher than those of the 50% SR and 25% SR treatments, with the lowest yield occurring with the control. On the other hand, with ES, grain yield observed with 125% SR was significantly higher than those of the SR, and 75% SR in that order. Unlike the other S sources, there were no significant differences in grain yield among 75% SR, 50% SR, 25% SR, and the control (Figures 1–3). Increasing the application rate of AS and MES beyond SR (125%_SR) did not result in yield increases. In a study involving S application rates, Carciochi et al. (2018, 2020) observed that S application rates greater than those required to attain the critical plant tissue S content did not increase productivity. Contrary to this finding, increasing the S application rate with ES consistently increased yield (Figure 1). Possibly, the insolubility and the relatively slow ES oxidation into the plant-available S form could be the reason for this observation of yield changes with ES application (Zhao et al., 2015).

Although the average yields observed in the trials conducted in Ghana (Figure 2) and Mali (Figure 3) were significantly lower than that observed in the United States, a similar trend in grain yield was observed for the S source and application rate as described in the United States. Since all other controllable factors, including the N application rate, were held constant, the differences observed in the corn yield observed with the S sources and application rates at all six sites could be attributed to differences in S availability. This was not unexpected because several studies have shown that S availability in soil enhances the effectiveness of N since both elements possess similar assimilation pathways and are key constituents of several physiological processes in plants, including the photosynthetic process, carbon assimilation, and electron transport chain, among others (Gigolashvili & Kopriva, 2014; Hooghe et al., 2013).

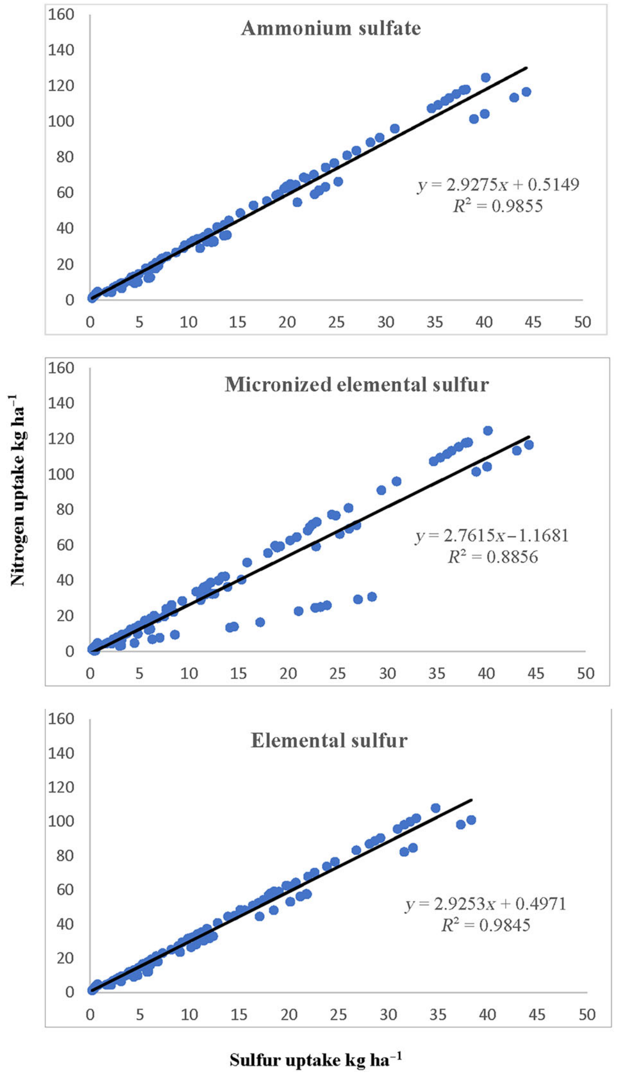

FIGURE 4 Relation of sulfur (S) and nitrogen (N) uptake in corn planted at six locations during the 2020–2022 growing seasons. AS, ammonium sulfate, ES, elemental sulfur; MES, micronized elemental sulfur.

3.2 | Sulfur availability on apparent nitrogen recovery efficiency

There were no significant variations ($p > 0.05$) among the experimental sites on S and N uptake as influenced by the S application rate during the study period at all six locations. Therefore, correlation analyses were performed on the pooled S and N data to ascertain the influence of S uptake on N uptake. Regardless of the S source and the experimental site, there was a strong positive correlation ($r > 0.88$) between the aboveground S and N uptake (Figure 4). When S uptake was low, particularly due to the source of S and the rate of application, N uptake was correspondingly low, and when S uptake increased, N uptake increased as a result. This suggests that irrespective of the location and the source of S fertilizer, N uptake was strongly linked to S availability to plants. This observation is consistent with that of other studies that N and S uptake closely mimicked one another (Carciochi et al., 2020). Sutradhar et al. (2017) showed that S and N utilization are closely associated because the assimilatory reduction reactions of both sulfate and nitrate are necessary for the synthesis of S-containing amino acids, and hence the uptake of one greatly influences the other. Studies have shown that the status of S strongly affects plants' N metabolism with S deficiency reducing NUE and vice versa (Maurya et al., 2005). Mehta et al. (2005) observed that the increasing availability of S progressively enhanced N uptake of maize. Thus, it was not surprising that in this study, among all the S fertilizer sources, the greatest N uptake was observed with the greatest S application rate at each location, with the lowest N uptake occurring with the control, which was deficient in S.

TABLE 3 Average apparent nitrogen recovery efficiency as influenced by different sulfur sources at different application rates during the 2020–2022 growing seasons.

Location	Sulfur rate (kg ha^{-1})	Ammonium sulfate (%)			Micronized elemental sulfate (%)			Elemental sulfur (%)		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
USA (Memphis, TN and Barton, AL	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6.25	34.8e	34.2e	33.5e	33.3e	33.8e	33.0e	33.8d	34.4d	35.3d
	12.5	40.3d	39.6d	37.3d	37.5d	37.2d	38.9d	34.3d	35.4d	36.9d
	18.75	65.3c	66.0c	65.9c	75.0c	74.8c	75.0c	37.8c	38.9c	38.9c
	25.0	77.4b	77.5b	73.1b	79.6b	80.6b	79.8b	45.7b	47.5b	48.3b
	31.25	80.9a	80.9a	76.3a	83.0a	84.7a	83.1a	50.2a	51.7a	53.4a
Tukey's HSD (0.05)		**2.22**	**2.15**	**2.52**	**2.95**	**2.92**	**3.01**	**3.59**	**3.74**	**3.88**
Ghana (Gushiegu and Karaga)	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7.50	36.4e	35.4e	35.1e	34.3e	34.9e	34.5e	33.9e	33.7e	34.0e
	15.0	45.6d	42.3d	40.9d	41.9d	40.1d	41.7d	37.7d	37.8d	38.2d
	22.5	50.7c	56.8c	47.5c	63.6c	64.4c	60.3c	41.5c	42.9c	41.4c
	30.0	65.2b	67.6b	63.2b	69.3b	68.4b	61.6b	50.8b	50.8b	47.0b
	37.5	67.3a	69.7a	66.7a	71.5a	70.8a	66.3a	53.6a	53.4a	50.5a
Tukey's HSD (0.05)		**1.88**	**1.56**	**2.14**	**1.89**	**2.08**	**2.66**	**2.36**	**2.17**	**2.40**
Mali (Sikasso and Kayes)	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	12.5	37.5e	36.7e	37.2e	35.7e	35.9d	35.7e	34.1e	34.3e	34.3e
	25.0	45.2d	44.7d	44.0d	41.5d	41.6c	40.8d	36.9d	37.1d	37.1d
	37.5	52.3c	55.7c	49.9c	64.4c	65.2b	55.0c	39.9c	41.1c	39.1c
	50.0	65.3b	65.6b	61.7b	68.3b	67.9ab	61.5b	47.9b	47.3b	44.7b
	62.5	67.1a	68.7a	64.5a	69.7a	68.9a	64.5a	49.7a	50.1a	47.6a
Tukey's HSD (0.05)		**1.47**	**1.87**	**1.96**	**1.26**	**1.33**	**2.05**	**1.77**	**1.92**	**2.03**

Note: Numbers in each cell are the average values of 72 replicates (6 sites × 3 years × 4 reps). Numbers in each row followed by the same letter are not significantly different ($p > 0.05$).

Abbreviations: HSD, honest significant difference; N/A, not applicable.

With the rising N fertilizer cost in recent times, N losses from the applied fertilizer are of great economic concern. In addition, N losses from agricultural lands could cause significant greenhouse gas emissions and N leaching to contaminate water bodies. It is, therefore, critical to evaluate the fate of applied N and determine the relative quantities recovered by plants. In this regard, we assessed the influence of the S application rate of the respective S sources (S availability) on the apparent N recovery efficiency. For the two sites in each country, there was no significant variation ($p > 0.05$) between them in terms of the apparent N recovery efficiency. Therefore, the apparent N recovery values were averaged across the two sites of each country for each S fertilizer source and analyzed separately for each growing season.

At the experimental sites in the United States, averaged across the three growing seasons, increasing the S application rate from 6.25 to 12.5 kg S ha^{-1}, with the AS as the S source, increased the apparent N recovery efficiency by 15.8%. Further increases of the S rate to 18.75, 25, and 31.25 kg S ha^{-1} resulted in 62%, 18.5%, and 4.5% increases in apparent N recovery efficiency, respectively (compared to the preceding S rate) (Table 3). In addition, with the MES, increasing the S application rate from 6.25 to 12.5 kg S ha^{-1} increased the apparent N recovery efficiency by 12.6%. Further increases in S rate to 18.75, 25, and 31.25 kg S ha^{-1} resulted in 100%, 6.1%, and 3.2% increases in apparent N recovery efficiency, respectively (compared to the preceding S rate) (Table 3). With the ES, increasing the S rate from 6.25 to 12.5 kg S ha^{-1} increased the apparent N recovery efficiency by 1.5%, and increasing the S rate further to 12.5, 18.75, 25, and 31.25 kg S ha^{-1} resulted in 10.2%, 20.9%, and 9.8% increases in apparent N recovery efficiency, respectively (compared to the preceding S rate). Similar results were observed for the trials established in Ghana and Mali (Table 3). Thus, regardless of the S source, experimental site, and the growing season, an increase in apparent N recovery efficiency occurred with increasing the rate of S application at each site. Salvagiotti et al. (2009) observed an increase in N recovery efficiency in wheat with S application and hypothesized that adequate S supply could promote better root growth to exploit the soil profile sufficiently to improve N recovery. This is consistent with the observation from other studies which have shown an

TABLE 4 Average agronomic nitrogen use efficiency as influenced by different sulfur sources applied at different rates during the 2020–2022 growing seasons.

Location	Sulfur rate (kg ha^{-1})	Ammonium sulfate (kg grains kg N^{-1})			Micronized elemental sulfate (kg grains kg N^{-1})			Elemental sulfur (kg grains kg N^{-1})		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
USA (Memphis, TN and Barton, AL)	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6.25	4.06e	2.68d	3.18e	4.00e	2.66e	3.15e	3.95e	2.54e	3.10e
	12.5	9.71d	10.3c	10.5d	9.50d	10.0d	10.3d	9.01d	9.53d	9.75d
	18.75	19.5c	20.0b	20.3c	22.1c	22.7c	23.1c	17.6c	18.1c	18.4c
	25.0	32.9b	35.3a	36.1b	32.9b	35.3b	36.1b	26.5b	28.4b	29.0b
	31.25	37.0a	37.4a	38.2a	37.0a	37.4a	38.2a	31.8a	32.2a	32.8a
Tukey's HSD (0.05)		**2.89**	**2.04**	**1.99**	**2.43**	**2.00**	**1.93**	**2.44**	**2.68**	**2.88**
Ghana (Gushiegu and Karaga)	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7.50	3.37e	3.11e	3.17e	2.51e	2.65d	2.32e	3.30e	3.01e	3.03e
	15.0	8.08d	12.2d	10.3d	5.74d	8.43c	7.08d	7.50d	11.3d	9.54d
	22.5	16.2c	23.7c	19.9c	12.8c	18.0b	15.2c	14.7c	21.4c	18.0c
	30.0	27.4b	41.9b	35.3b	19.8b	29.0a	23.5b	22.0b	33.7b	28.3b
	37.5	30.8a	44.4a	37.4a	22.2a	30.7a	25.9a	26.5a	38.2a	32.1a
Tukey's HSD (0.05)		**2.44**	**2.19**	**1.98**	**2.05**	**2.26**	**2.31**	**2.86**	**3.15**	**3.02**
Mali (Sikasso and Kayes)	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	12.5	2.03e	1.99d	2.87e	2.00e	1.98e	2.86e	1.98e	1.91e	2.75e
	25.0	4.91d	7.81c	9.44d	4.75d	7.55d	9.14d	4.51d	7.16d	8.66d
	37.5	9.11c	13.9b	16.9c	11.1c	17.0c	20.5c	8.81c	13.6c	16.3c
	50.0	16.5b	26.5a	32.0b	16.5b	26.5b	32.0b	13.2b	21.3b	25.7b
	62.5	18.5a	28.1a	33.9a	18.5a	28.1a	33.9a	15.9a	24.2a	29.2a
Tukey's HSD (0.05)		**2.54**	**2.78**	**1.76**	**1.94**	**1.38**	**1.83**	**2.16**	**2.35**	**2.91**

Note: Numbers in each cell are the average values of 72 replicates (6 sites × 3 years × 4 reps). Numbers in each row followed by the same letter are not significantly different ($p > 0.05$).

Abbreviations: HSD, honest significant difference; N/A, not applicable.

increase in apparent N recovery with increased S availability to plants. This was not surprising since S is an essential plant nutrient that affects N assimilation directly as a constituent of enzymes involved in N metabolism (Abadie & Tcherkez, 2019).

3.3 | Effect of sulfur availability on agronomic nitrogen use efficiency

There were highly significant ($p < 0.01$) S source and application rates on ANUE at all six experimental sites during the entire duration of the study. Consistent with the corn yield, the ANUE values in the trials conducted in the United States (average from the Memphis, TN, and Barton, AL sites) were the greatest followed by those from Ghana (Gushiegu and Karaga) and Mali (Sikasso and Kayes) in that order (Table 4). These differences in ANUE values due to location effect could be attributed to differences in corn hybrid used, physico-chemical soil properties, and agri-environmental conditions, among other variables. These differences notwithstanding, the effect of S availability on ANUE followed a similar trend at all locations during the duration of the study.

Within a particular country, there was no significant location variation in ANUE; therefore, in each country, the ANUE values were averaged across the two experimental sites within the country. However, there were significant S source and year effects on ANUE due to the S application rate, but location × year interaction was not significant. As a result, the ANUE data were pooled separately for each year and S fertilizer source (Table 4).

At the experimental sites in the United States, averaged across the three growing seasons, increasing the S application rate from 6.25 to 12.5 kg S ha^{-1}, with the AS as the S source, increased ANUE by 139%. When the S application rate was further increased to 18.75, 25, and 31.25 kg S ha^{-1}, agronomic NUE increased by 100%, 68.7%, and 12.5% increases in ANUE, respectively (compared to the preceding

S rate) (Table 4). With the MES, increasing the S application rate from 6.25 to 12.5 kg S ha^{-1} increased ANUE by 137%. Further increases in the S rate to 18.75, 25, and 31.25 kg S ha^{-1} resulted in 132%, 48.9%, and 12.5% increases in ANUE, respectively (compared to the preceding S rate) (Table 4). With the ES, increasing the S rate from 6.25 to 12.5 kg S ha^{-1}, increased ANUE by 98%, and further increases of the S rate to 12.5, 18.75, 25, and 31.25 kg S ha^{-1} resulted in 95.3%, 50.6%, and 20%, respectively (compared to the preceding S rate). Similar results were observed for the trials established in Ghana and Mali (Table 4). The combined data show that regardless of the S source, or the growing season, and location of the experiment, ANUE is enhanced with S availability to plants. Increasing ANUE is a needed strategy not only to increase growers' income by reducing the cost of production (Aulakh & Malhi, 2004), preventing excessive N application, and minimizing N losses, which could eventually disrupt the ecosystem function (Ladha et al., 2005), but will be pivotal in meeting the ever-increasing food and fiber demand (Fixen et al., 2015).

4 | SUMMARY AND CONCLUSIONS

For the entire duration of the study, the agronomic effectiveness of the S sources followed the order: AS ≥ MES > ES at all experimental sites, and that emanating from the application rate followed the order: 125% SR = SR > 75% SR > 50% SR > 25% SR > control with AS. With MES, it was in the following order: 125% SR = SR = 75% SR > 50% SR > 25% SR ≥ control, and with ES, the following order was observed: 125% SR > SR > 75% SR = 50% SR = 25% SR = control. Regardless of the S source and the experimental site, there was a highly significant strong positive correlation ($r > 0.88$) between the aboveground S and N uptake. Increasing the S application rate resulted in increasing apparent N recovery efficiency and ANUE at each site. The combined data suggest that the efficiency of applied N fertilizer sources can be improved significantly by increasing S availability in soils. With the rising N fertilizer costs in recent times, N losses from the applied fertilizer are of great economic and environmental concern. Thus, increasing ANUE is a necessary strategy not only to prevent excessive N application, increase farm income in crop production systems, and reduce N losses to the environment that could disrupt the ecosystem function but also meet the ever-increasing food and fiber demand.

AUTHOR CONTRIBUTIONS

Sampson Agyin-Birikorang: Conceptualization; data curation; investigation; methodology; supervision; writing—original draft; writing—review and editing. **Cissé Boubakry**: Investigation; methodology; validation; writing—original draft; writing—review and editing. **Davie M. Kadyampakeni**: Data curation; formal analysis; methodology; validation; writing—original draft; writing—review and editing. **Raphael Adu-Gyamfi**: Data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Rachel A. Chambers**: Data curation; validation; writing—original draft; writing—review and editing. **Ignatius Tindjina**: Data curation; investigation; methodology; validation; writing—original draft; writing—review and editing. **Abdul-Rahman A. Fuseni**: Data curation; methodology; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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