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Soil Fertility and Crop Nutrition

Improving agronomic effectiveness of elemental sulfur to increase productivity in sulfur-deficient soils

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Abstract

Elemental sulfur (ES), a byproduct of oil and gas processing, could be an alternate sulfur (S) fertilizer source for crop production if its bioavailability is improved. Increasing the specific surface of ES by reducing its particle size can accelerate ES oxidation to enhance its bioavailability. In field trials at six locations across three countries: two each in the United States, Ghana, and Mali, we determined the agronomic effectiveness of micronized ES (MES). Specific objectives were to quantify (i) corn (*Zea mays* L.) productivity, (ii) S recovery, and (iii) residual soil S concentration; following MES application, compared to ammonium sulfate (AS), a commercially available sulfate fertilizer, at four application rates—(i) locally recommended sulfur application rate (SR), (ii) 50%_SR, (iii) 75%_SR, and (iv) 125%_SR—and a control where no S was applied. Averaged across all sites and in the three growing seasons, AS at 50%_SR increased corn yield by ≤8% relative to control. Increasing to 75%_SR, SR, and 125%_SR resulted in 12%, 26%, and 28% yield increases, respectively. Applying MES at 50%_SR increased yield by ≤6%, and at 75%_SR, yield increased by ≤26%. Increasing the S application rate to SR and 125%_SR resulted in marginal yield increases. The combined data suggest that MES can be applied at a reduced rate of 75_SR to achieve similar yields as AS applied at SR. We conclude that MES could be an efficient S fertilizer alternative. However, economic analysis is needed to determine the potential profitability of using MES fertilizer products for crop production.

1 | INTRODUCTION

Sulfur (S), one of the essential plant nutrients, has received increased attention in recent times because of the frequently occurring S deficiency in agricultural soils worldwide, which has been recognized as a significant constraint in crop production. Sherer (2009) reported that the declining S levels in soils are direct or indirect results of the regulation of SO_2 emissions from fossil fuels combustion and industrial activities to the atmosphere through the enactment of environmental laws, which significantly affects S deposition from air to soils. As a result of stricter regulations and international agreements on emissions, further decreases in SO_2 emissions are likely to occur in the near future, and S deficiency will become a common occurrence in agricultural soils (Riley et al., 2002). Kamprath and Jones (1986) and Krishnamoorthy (1989) also observed that adopting high-analysis fertilizers

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Abbreviations: AEZ, agroecological zone; AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur; SR, sulfur application rate.

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containing little or no S, and low S returns with recycled farmyard manure have caused a widespread S deficiency among agricultural soils. Other studies have also shown that using of high-yielding crop varieties and intensive farming practices that result in S mining from the soil and the declining use of S-containing pesticides and fungicides are major causes of S deficiency in soils (Kang & Osiname, 1976; Scherer, 2009).

Even though detecting S deficiencies in most field crops can be problematic because symptoms are not exclusively obvious, substantial yield responses have been reported with S application, even in quantities as small as 11 kg S ha^{-1} (Sutar et al., 2017). Studies have shown increases in crop yields of 5%–50% in response to S application (Kaur et al., 2019). Kugbe et al. (2019) and Kovar (2021) reported maize yield losses of between 10% and 30% due to inadequate S supply, which is consistent with the observation of Agyin-Birikorang et al. (2022, 2023) that up to 28% maize yield loss occurred due to S deficiency. In soils deficient in S, the use efficiency of macronutrient fertilizers is substantially low, which results in the anticipated high yield potential and profitability of most crop hybrids not being attained, regardless of all other essential nutrients supplied in adequate quantities (i.e., Liebig's "law of the minimum") and exceptional farm-management practices being followed (Kaur et al., 2019). Several studies have shown that S also improves the quality of most crops due to its effect on oil synthesis and protein metabolism (Krishnamoorthy, 1989; Patil et al., 1998). Thus, S fertilization is critical for increased and sustained productivity in S-deficient soils.

For several decades, sulfate-containing fertilizers have been the most commonly used S sources for crop production globally. Although elemental sulfur (ES), which is obtained from the processing of oil and gas as a by-product, could be a cheaper alternative S fertilizer source, untreated ES tends to be hydrophobic and sometimes inert that requires oxidation to the sulfate form before it can be utilized by plants as S source (Germida & Janzen;, 1993). Studies have shown that the ES oxidation to the sulfate form is a natural process carried out by soil microorganisms and, as such, primarily controlled by soil and environmental conditions and the particle size of ES (Germida & Jazen, 1993; Watkinson Blair, 1993). To accelerate the ES oxidation process, S-oxidizing microbes need access to the surface of ES. Since the specific surface of ES can be exponentially increased by decreasing the particle size of ES, doing so will ultimately allow for a more rapid conversion of ES to sulfate. One way to achieve this is to dissolve ES in an appropriate solvent, for example, anhydrous ammonia, and precipitate the resultant solution to produce ultrafine ES particles of ≤50 μm in diameter, likely improving ES's agronomic effectiveness. In addition to making S available for crop production, this process will have the advantage of reducing S losses as those commonly associated with conventional sulfate fertilizers. Thus, the micronized elemental sulfur (MES) can potentially increase the agronomic effectiveness of applied ES, perceivably contributing to environmental sustainability by minimizing S losses, as observed with most sulfate-containing fertilizers. Therefore, the overall objective of this study was to determine the agronomic effectiveness of MES relative to commonly used commercial sulfate fertilizers. Specific objectives were to quantify (i) corn (*Zea mays* L.) productivity, (ii) S recovery efficiency (SRE), and (iii) residual soil S concentration; with the application of MES-containing fertilizer product. In this study, we compared the agronomic effectiveness of MES with a commercially available S fertilizer product, ammonium sulfate (AS), and with untreated ES at four application rates and control where no S was applied.

Core Ideas

- Particle size reduction can improve the bioavailability of elemental sulfur (ES), making it an effective sulfur (S) fertilizer.
- At the recommended S rate, micronized elemental sulfur (MES) was as effective as ammonium sulfate (AS) as an S fertilizer source.
- MES was more effective than AS at a reduced (75%) sulfur application rate.
- MES had additional environmental benefits of reducing S losses as those associated with AS.
- MES could be an efficient S source for sustainable and profitable crop production in S-deficient soils.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

Three-year field experiments were conducted during the 2020–2022 growing seasons on S-deficient soils at six locations across three countries: two each in the United States, Ghana, and Mali. In the United States, one experiment was sited at a private farm in Milan, TN (35˚56′06.8″ N, 88˚45′13.2″ W) and the other at Barton, AL (34^{o}44′35.2″ N, 87^{o}54′02.4″ W). The soil at the Milan site is classified as Loring silt loam (Fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs), and that at the Barton, AL site is a weathered Ultisol, classified as Fine, kaolinitic, thermic Rhodic Paleudults, with a silt loam texture, typical soil texture of farms in the southern United States (Soil Survey Staff, 2009). The site at Barton was under the conventional plow system, whereas that of Milan was under the no-till conservation system. Trials in Ghana were established in Karaga

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TABLE 1 Selected physicochemical properties of the soil at each experimental sites.

		Ghana		**United States**		**Mali**	
Characteristics	**Units**	**Karaga**	**Gushiegu**	**Barton, AL**	**Milan, TN**	**Sikasso**	**Kayes**
pH-H_2O		6.84 ± 0.11	6.52 ± 0.20	6.30 ± 0.24	6.86 ± 0.18	6.48 ± 0.21	6.15 ± 0.22
Sand	g kg^{-1}	480	450	310	290	560	680
Silt		350	360	500	500	260	80
Clay		170	190	190	210	180	240
Organic C		3.45 ± 0.38	3.79 ± 0.41	7.34 ± 1.02	5.24 ± 0.17	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	0.24 ± 0.24	2.14 ± 0.18	1.92 ± 0.12
Ammonium-N		8.44 ± 0.92	5.50 ± 0.62	4.10 ± 0.47	0.84 ± 0.91	3.05 ± 0.19	2.46 ± 0.25
Available P (Pi-P)		4.28 ± 0.44	2.88 ± 0.21	8.00 ± 0.96	7.60 ± 0.69	5.13 ± 0.66	4.17 ± 0.45
Sulfate-S		2.03 ± 0.11	1.12 ± 0.17	2.21 ± 0.62	3.22 ± 0.35	1.96 ± 0.12	1.32 ± 0.09
Zinc		0.24 ± 0.04	0.63 ± 0.04	0.21 ± 0.02	0.13 ± 0.01	0.46 ± 0.03	0.32 ± 0.02
Boron		0.37 ± 0.02	0.43 ± 0.04	0.32 ± 0.04	0.43 ± 0.05	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	0.20 ± 0.02	0.16 ± 0.01	0.21 ± 0.02
Exchangeable Ca		1.31 ± 0.11	1.43 ± 0.12	3.94 ± 0.53	4.00 ± 0.38	2.04 ± 0.19	3.16 ± 0.34
Exchangeable Mg		0.75 ± 0.06	0.93 ± 0.12	1.63 ± 0.16	2.69 ± 0.12	0.86 ± 0.09	0.92 ± 0.10
CEC		3.14 ± 0.31	2.18 ± 0.12	5.19 ± 1.27	6.92 ± 0.52	1.68 ± 0.14	1.92 ± 0.12

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

(9°55′24.5″ N, 0°25′ 32.6″ W) and Gushegu (9°43′09.3″ N, 0°19′12.7″ W), both located within the Guinea Savanna agroecological zone (AEZ). The soil at the Karaga site is Luvisols, and the soil at the Gushiegu site is Plinthosols (ISSS/ISRIC/FAO, 1998). The trials in Mali were established in Sikasso (11°19′02.1″ N, 5°40′03.1″ W) in the Southern Sudan Savanna AEZ and Kayes (14°27′46.2″ N, 11°26′44. 3″ W) in the Sahel AEZ (Akinseye et al., 2016). The soil at the two sites is classified as Ferric Lixisols (ISSS/ISRIC/FAO, 1998).

Before starting the study, soil samples were collected from each plot to characterize the initial physicochemical properties of the soil. Each site was partitioned into 24 subunits, and a composite soil sample (mixing 20 2.5-cm diameter core samples) was collected from the 0- to 15-cm depth of each subunit. Selected physicochemical characteristics of soil at each location are presented in 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 | Production of micronized elemental sulfur

The MES was produced using a proprietary and patented process that involved a two-step process: (i) dissolution of ES in S-solvent and (ii) precipitation of the resultant solution. During this process, ES was dissolved in anhydrous ammonia to form a true S solution. The ES–ammonia solution was then pressurized at room temperature for 48 h, and the release of the pressure caused volatilization of the hydrated ammonia and precipitation of ES with particle sizes ranging from 10 to 50 µm, with 20 µm being the average particle size. The resultant MES product was co-granulated with ammoniacal fertilizers for S to spread out evenly amongst more granules for ease of application and a more uniform distribution in the field.

2.3 | Experimental setup

The trial established at each site was a 3 × 5 factorial experiment (three S sources and five application rates). The S fertilizer sources used for the study were as follows: (i) MES (14.5% S, 32% N), (ii) AS (24% S, 21% N), and (iii) untreated ES (92% S). The sulfur application rates (SRs) were as follows: (i) site-specific recommended S rate (SR), (ii) half of the recommended S rate (50% SR), (iii) three-fourth of the recommended S rate (75% SR); and (iv) 1.25 of the recommended S rate (125% SR). Thus, in the US sites, S was applied at 25, 12.5, 18.75, and 31.25 kg S ha^{-1}, respectively; in the Ghana sites, S was applied at 30, 15, 22.5, and 37.5 kg S ha^{-1}, respectively; and in the Mali sites, S was applied at 50, 25, 37.5, and 62.5 kg S ha^{-1} respectively. A control treatment in which no S was applied was included in the study. The treatments were organized in a split-plot

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

	No. of wet days			Total precipitation (mm)			Temperature range (˚C) Minimum			Maximum		
Location	2020	2021	2022	2020	2021	2022	2020	2021	2022	2020	2021	2022
Milan, TN	52	54	57	1,333	1,354	1,420	12.8	13.1	13.8	28.4	34.5	31.2
Barton, AL	53	51	49	1,240	1,208	1,175	14.5	12.4	14.7	37.2	38.4	38.8
Gushiegu	54	52	50	1,036	1,104	1,072	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

randomized complete block design, with the S sources occupying the main plots and the SRs occupying the subplots, with four replications per treatment.

Based on site-specific recommended rates, all other limiting essential nutrients were applied in sufficient quantities, such that S remained the only limiting nutrient. N, phosphorus (P), potassium (K), and Zinc (Zn) were all applied at the recommended rates for each site. 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). Since the AS and MES fertilizer products contained N (21% N and 32% N, respectively), adequate quantities were applied to supply all the required S as determined for each treatment. The shortfall in N was compensated for with urea (46% N).

2.4 | Planting of corn

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 by 16.5 cm, resulting in a seeding rate of 79,500 plants ha^{-1}. At the two sites in Ghana, medium-maturing (115 days) and drought-tolerant corn hybrid (Pan 53) was planted at a spacing of 80 cm × 20 cm, resulting in a plant population 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. At the Kayes site, an early-maturing (90 days), Striga-resistant corn hybrid (Mata, TZE-Y Pop DT STRC4 × TZEI 13) was planted. Both corn hybrids were planted at a spacing of 75 cm × 25 cm, resulting in a plant population of 66,670 plants ha^{-1}.

2.5 | Measurements, data collection, and calculations

Corn ear leaves were sampled from 10 plants randomly selected from the four middle rows of each plot at the initial silk stage to determine tissue S content as described in Kovar (2021). At maturity, the four middle rows of each plot were harvested manually, de-husked, and then shelled. 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). Randomly selected 10 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. The biomass and grain samples were oven-dried, and analyzed to determine tissue S content, following the procedure described in Kovar (2021). The product of the total biomass and tissue S content was used to estimate S uptake. Apparent SRE was assessed with a modification of the method described in Agyin-Birikorang et al. (2020):

$$\mathrm{SRE}(\%) = \frac{(\mathrm{TSUs} - \mathrm{TSUc})}{Q} \times 100,$$

where TSU is total (grain + biomass) S uptake (kg ha^{-1}): TSUs is the TSU of S-fertilized treatments, TSUc is the TSU of treatment with no S supply (kg ha^{-1}), and Q is the quantity of S applied (kg ha^{-1}).

2.6 | Postharvest soil sampling and analyses

Soil samples were collected after corn harvest in each growing season, following the procedure described above for the initial soil characterization, and analyzed for S to determine residual soil S concentration as influenced by the S fertilizer sources.

2.7 | Statistical analyses

Analysis to evaluate the variation of the experimental sites was performed with the analysis of variance (ANOVA) mixed model, in which all the factors were handled as fixed effects and the error terms as random effects. This was followed by an analysis to test the growing season's impact on the treatments. This second analysis was also performed with the ANOVA mixed model, where the random factor was the residual term.

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The ANOVA model's homogeneity of variances and normality assumptions were verified with the Levene's test residual plots and the Kolmogorov–Smirnov procedure, respectively (Littell et al., 1996). A significant variation among the experimental sites and growing seasons were observed. Therefore, ANOVA for the treatment effects on yield, SRE, and residual soil S were performed separately for each experimental site and growing season with a generalized linear mixed model (PROC GLIMMIX, SAS 9.4, SAS Institute Inc., 2018). This analysis designated treatment as a fixed effect, whereas replications and their interactions were handled as random effects (Littell et al., 1996). Treatment means were separated with Tukey's honest significant difference test, and probability levels less than 0.05 ($p < 0.05$) were designated as significant.

3 | RESULTS AND DISCUSSION

3.1 | Ear-leaf tissue sulfur concentration as influenced by the sulfur sources

In this study, a critical ear-leaf tissue S content of 1.5 g kg^{-1} (0.15%) was designated as the sufficiency level, below which we envisaged that corn productivity could be negatively impacted. This is in line with Kamprath and Jones (1986) who reported that tissue S content of 0.15% is a critical S sufficiency level, below which proper growth and development of the plant are negatively affected. In other studies, Bryson and Mills (2014) also confirmed that the ear-leaf tissue S content of ≥0.15% is sufficient for corn's proper growth and development. Similarly, in a 2-year study at 10 experimental sites in North Dakota, Kaur et al. (2019) arrived at the same conclusion. On the other hand, in a study in Nigeria, Kang and Osiname (1976) reported ear-leaf tissue S content of 0.14% as the critical level for corn growth and development. This seemingly inconsistent critical S concentration limits could be attributed to differences in extractant used, soil characteristics, and corn variety/hybrid used, among others.

Except for ES, a strong positive correlation ($r \geq 0.89$) existed between the SR and ear-leaf tissue S content with AS and MES. This suggests that increasing the SR increased soil solution S concentration available for plant uptake. Averaged across the three growing seasons and in the six experimental sites, the lowest ear-leaf tissue S concentration consistently occurred with the control, and the ES source at all SRs was consistently below the critical S concentration (Figures 1–3). This observation is consistent with that of other studies that ES is essentially inert and rarely water-soluble, which requires oxidation to sulfate to become plant-available, but the oxidation process by which ES is converted to sulfate is relatively very slow (Germida & Janzen, 1993; Watkinson & Blair, 1993). Therefore, it was not out of place that lower ear-leaf tissue S concentration occurred with the ES source. With AS, application rates less than the recommended quantities resulted in ear-leaf tissue S content below the critical level.

While several studies have shown that AS, composed of salt, is highly soluble and a great source of immediately available S (Powlson & Dawson, 2022; Riley et al., 2002), the low ear-leaf tissue S content at application rates less than SR suggest that the quantities of AS applied were either not sufficient to ensure proper growth and development for the crop, or a large portion of the applied AS was lost from the soil due to its high solubility. On the other hand, application of AS at a minimum of SR resulted in ear-leaf tissue S content at or above the critical limit (Figures 1–3). With MES, an application rate ≥75%_SR significantly increased the tissue S content to levels considered sufficient to sustain corn productivity. Since ES oxidation is a natural process controlled by soil microbes, soil, and environmental conditions such as moisture and temperature that play significant roles in plant growth also affect the ES oxidation rate. Therefore, in cold and dry environments, MES remains in the elemental form, and in warm and moist conditions, when soil biological activity increases, the conversion of MES to sulfate is rapid. This creates a "controlled release" of S from MES to coincide with plant S uptake since similar environmental factors influence both processes, thereby maintaining crop S nutrition throughout the growing season. Also, due to this controlled-release characteristic, MES is likely to keep S within reach of young developing roots not sufficiently deep to take up nutrients that have moved to lower depths, as is the case for sulfate fertilizers.

3.2 | Effect of the sulfur sources and application rates on corn yield

There was a significant ($p < 0.05$) location variation on corn yield; however, this notwithstanding, in all six locations, the effect of the growing season (year) on corn yield was highly significant ($p < 0.01$). Also, significant differences among the S sources ($p < 0.05$) and application rate ($p < 0.01$) were observed. However, S source × S rate interaction, and year × S source × S rate interaction were not significant ($p > 0.05$).

In both locations in the United States (Milan, TN and Barton, AL), grain yield was significantly lower in the 2022 growing season than in the 2020 and 2021 growing seasons (Figure 4). On the other hand, in the Ghana locations, grain yield observed in the three growing seasons followed the order 2021 > 2022 > 2020 (Figure 5), but in the Mali locations, it was 2022 > 2021 > 2020 (Figure 6).

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 source and application rate on

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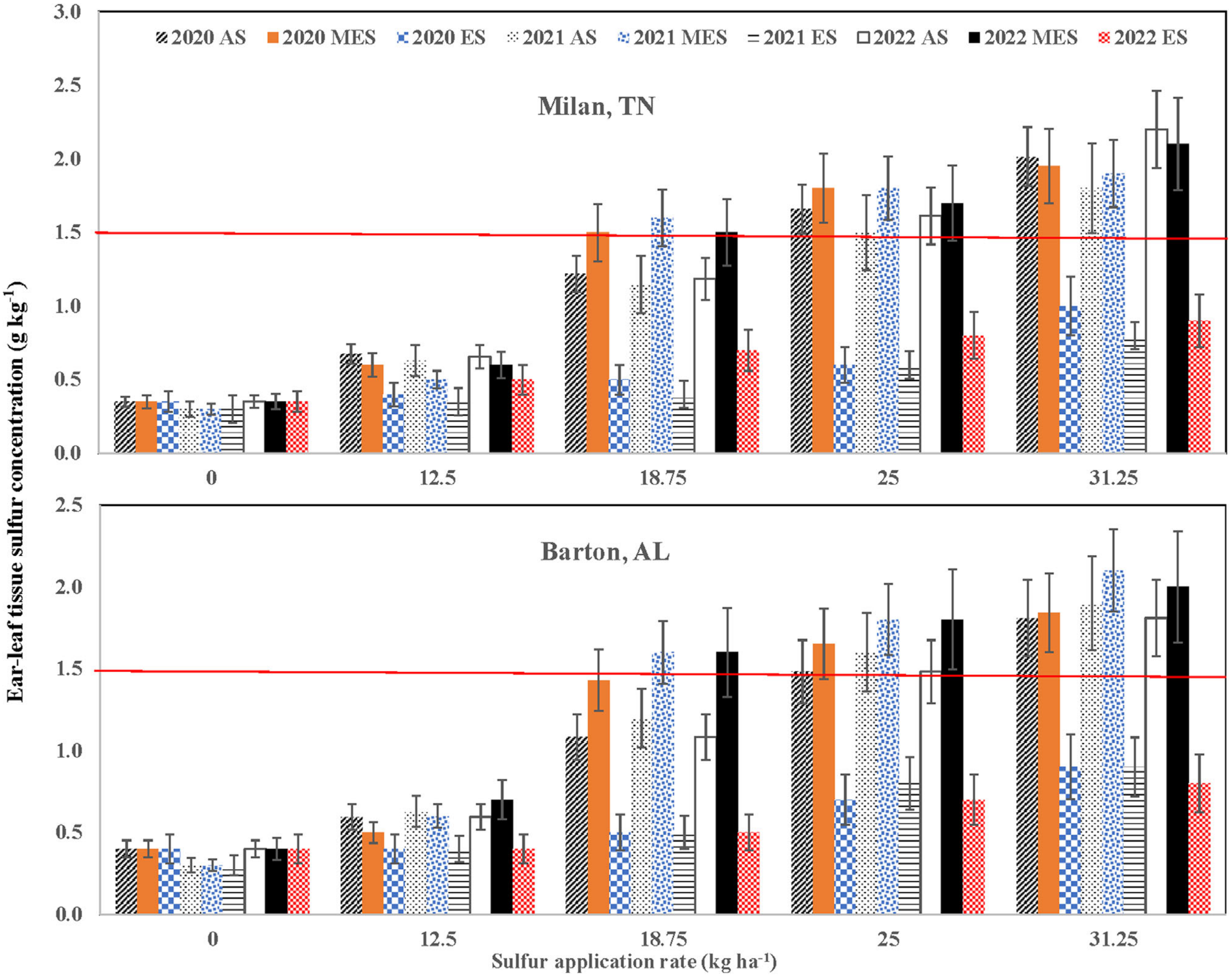

FIGURE 1 Ear-leaf tissue sulfur concentration of corn grown in the Milan, TN and Barton, AL sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. The horizontal line within the graph is a visual representation of the critical ear-leaf tissue sulfur concentration for corn. AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur.

yield followed similar trends. In the US locations, averaged across the growing season, there were no significant differences ($p > 0.05$) between AS and MES in yield, which were significantly greater than that observed with ES (Figure 4). At the recommended SR, the average grain yield with AS and MES was 8.32 Mg ha^{-1} and 8.28 Mg ha^{-1}, respectively, and that of ES was 6.86 Mg ha^{-1}. Increasing the application rate of AS and MES beyond SR (125%_SR) did not result in significant yield increases. In a study involving SRs, Carciochi et al. (2018, 2020) observed that SRs greater than those required to achieve the critical tissue S content did not increase productivity. However, it caused S content to increase because the additional dry matter buildup was too small to have a dilution effect. Contrary to this observation, with ES, increasing the SR resulted in an increase in yield (Figure 4). Possibly, the low solubility 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 (Germida & Janzen, 1993; Watkinson & Blair, 1993). Although average yields observed in the trials conducted in Ghana (Figure 5) and Mali (Figure 6) 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 for the United States. The combined yield data suggest that MES could be as effective as AS when applied at the recommended S rate but was more effective at a slightly reduced rate (75% of the recommended S rate) than AS. This could be explained by the controlled release characteristic of MES to match S release to the S demand at different growth stages of the crop. On the other hand, the comparatively lower yield with AS at 75%_SR suggests that due to the fast solubility of AS, some portions could have been lost from the soil, making the remaining S content in the soil inadequate to meet the crops' S demand, particularly during the latter stages of growth.

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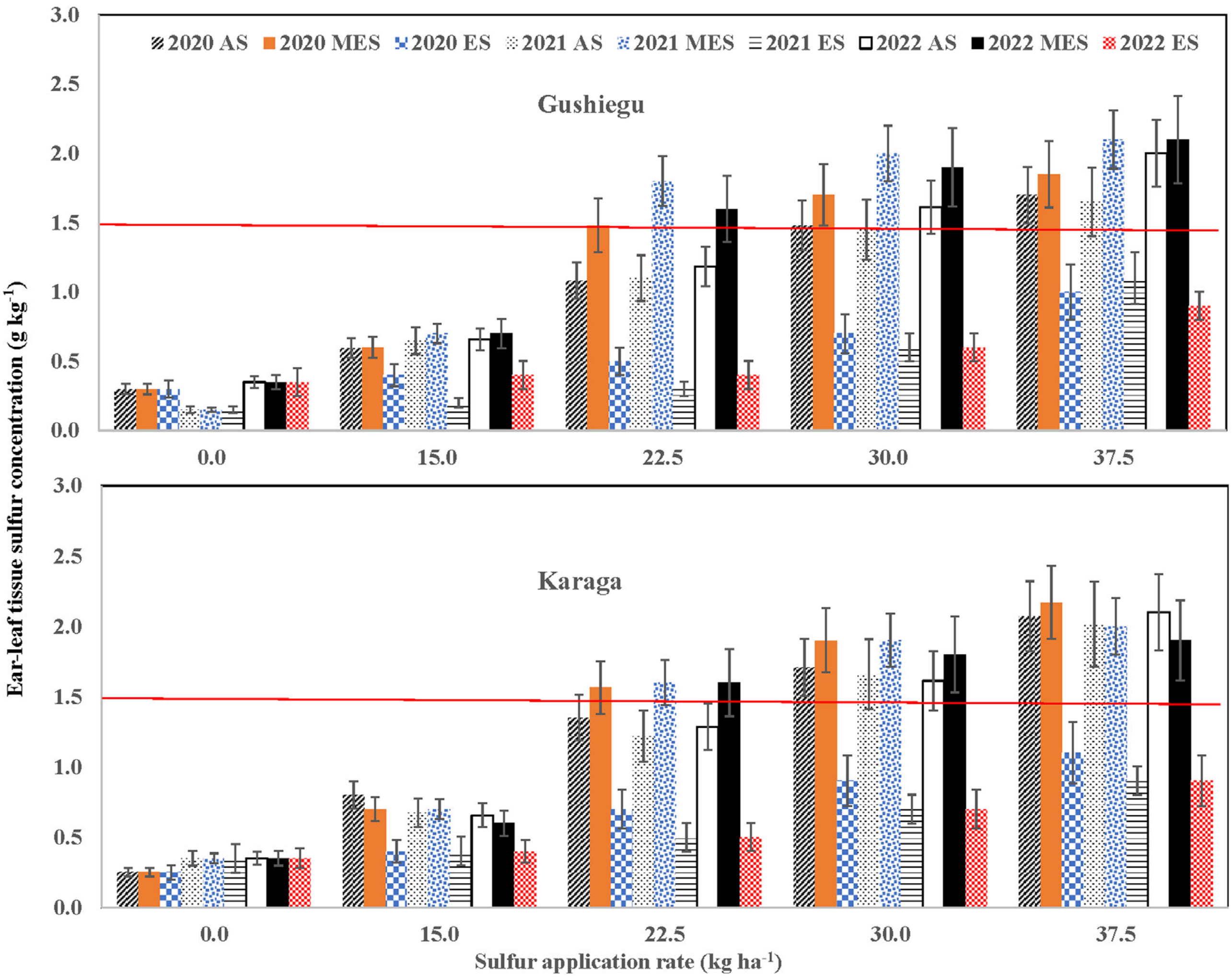

FIGURE 2 Ear-leaf tissue sulfur concentration of corn grown in the Karaga and Gushiegu (Ghana) sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. The horizontal line within the graph is a visual representation of the critical ear-leaf tissue sulfur concentration for corn. AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur.

3.3 | Apparent sulfur recovery efficiency

Economic and environmental concerns have increased the need to better understand the fate of applied fertilizer sources in crop production systems. Therefore, the recovery of the applied sources of S fertilizer products was calculated to assess the fate of the applied S fertilizer sources. For the two sites in each country, there was no significant variation ($p > 0.05$) between them in SRE for the entire duration of the study, and the interaction of S source × SR on SRE was not significant ($p > 0.05$). Therefore, the apparent S recovery values were averaged across the two sites of each country for the study period and analyzed separately (Table 3).

Consistent with other studies, a strong negative correlation ($r > -0.88$) between SRs and SRE for the AS and MES sources was observed, with increasing SRs resulting in decreasing SRE. This suggests that the crops could not absorb most of the applied S when high S doses were applied, which could result in significant S losses.

The average apparent SRE followed the order: MES > AS > ES (Table 3). The relatively high apparent SRE with the MES could be due to the oxidation of the micro-sized ES particles at a rate that matched crop S uptake and, thus, minimized S losses from fields, mainly through leaching losses. This result suggests that barring unfavorable environmental conditions, including drought and extreme temperatures, MES could be an efficient S source for crop production in S-deficient soils. The lowest apparent SRE among the S fertilizer treatments occurred with ES, suggesting that the crop did not utilize most of the applied S. Although this could be a financial loss to the farmer in the season when the fertilizer was applied, the unoxidized ES could still be available eventually for subsequent cropping if the low recovery is simply due to slow oxidation and the

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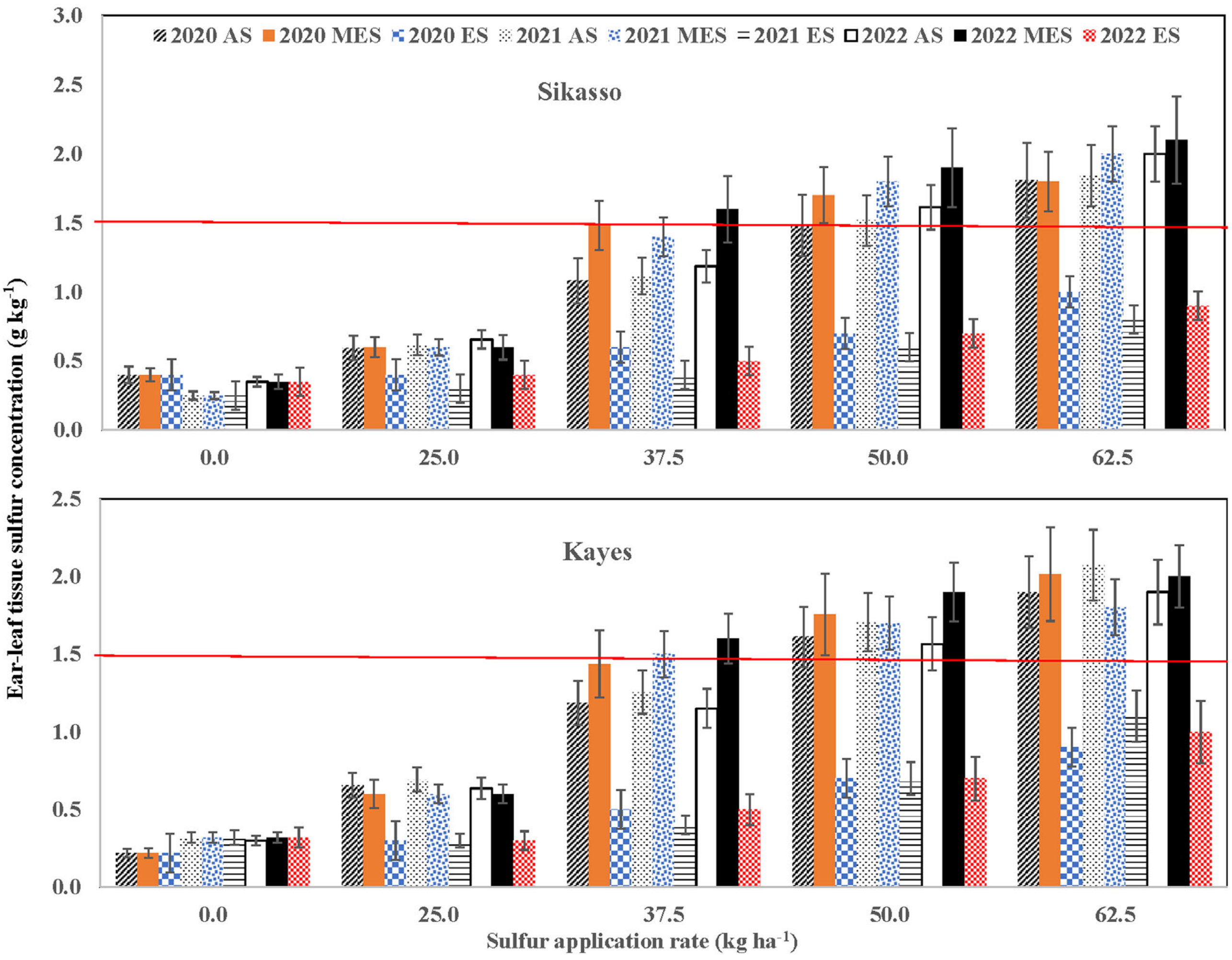

FIGURE 3 Ear-leaf tissue sulfur concentration of corn grown in the Sikasso and Kayes (Mali) sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. The horizontal line within the graph is a visual representation of the critical ear-leaf tissue sulfur concentration for corn. AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur.

ES remains in the soil without being lost through surface runoff.

3.4 | Apparent sulfur losses from the sulfur sources

Across all locations and for entire duration of the study, postharvest sulfate (SO_4-S) concentration showed a decrease in the topsoil for all treatments, compared with the initial SO_4-S content of the soil (Table 1 vs. Table 4), suggesting that no SO_4-S retention occurred in the soil during the study period. This is consistent with other studies: Kirchmann et al. (1996) did not observe any S build-up in the soil after 35 years of AS application at 91 kg S ha^{-1} annually. Similarly, in a long-term study with AS application at 52–220 kg S ha^{-1} annually for >150 years, Knights et al. (2000) did not observe a significant increase in soil S concentration.

With respect to the observed apparent SRE values, the greatest S buildup in the soil among fertilizer treatments was expected to occur with the ES treatment. However, in contrast with this expectation, the smallest residual SO_4-S concentrations rather occurred with the ES treatment (Table 4). This prompted us to measure the postharvest total S concentration of the soil and observed that the highest total S concentration occurred with the ES treatment (data not presented). This suggests that most of the applied ES did not oxidize to SO_4-S for plant uptake but remained in the ES form. This accumulated ES in the soil could be beneficial to subsequent crops. Although the greatest apparent SRE occurred with the MES, residual topsoil SO_4-S concentrations were still the highest with MES among the three S sources (Table 4). The MES initially had all its S content in the elemental form at micro-sized particles, which had to be oxidized over time to release plant-available SO_4-S to the plant, thereby synchronizing S supply to the plant's S demand and, thus, minimizing

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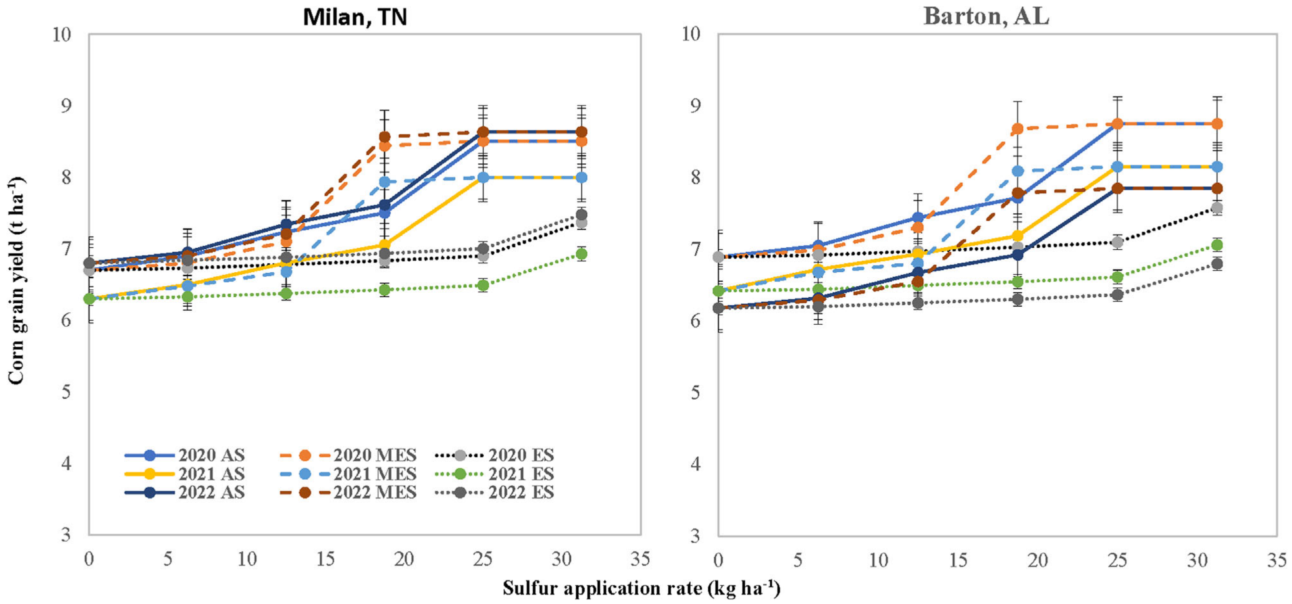

FIGURE 4 Corn grain yield from the Milan, TN and Barton, AL sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur.

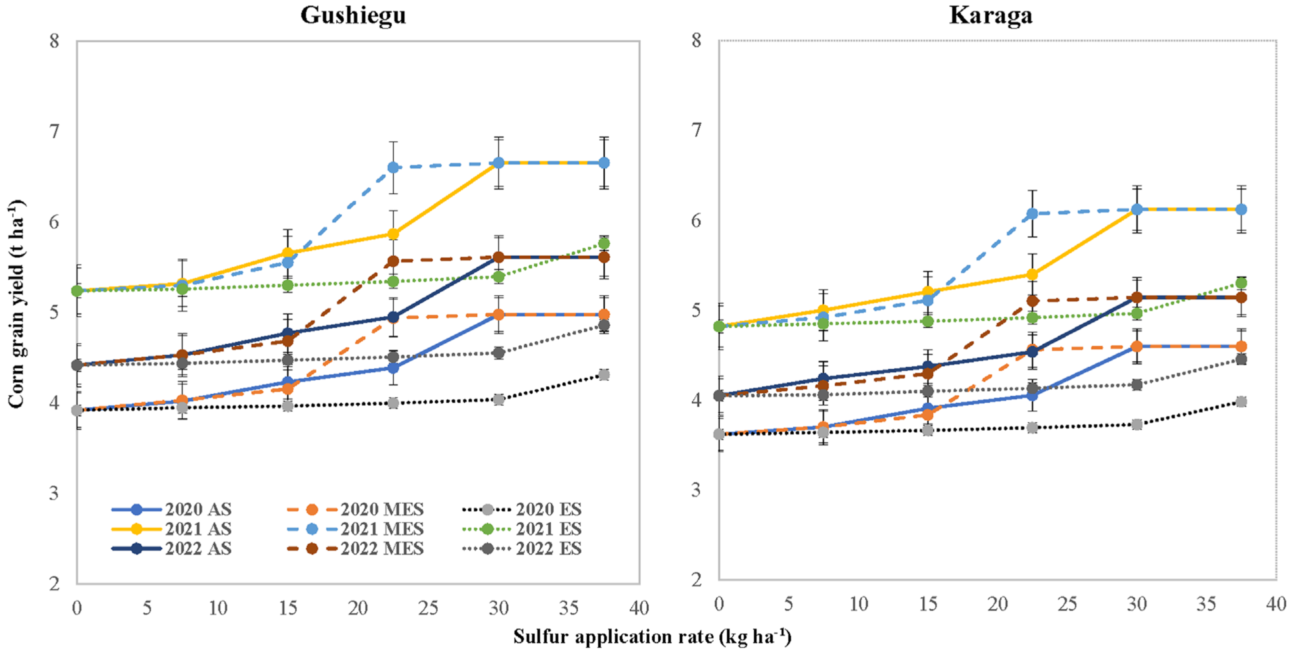

FIGURE 5 Corn grain yield from the Karaga and Gushiegu (Ghana) sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur.

S losses. The lower postharvest SO_4-S concentration with AS than MES (although S recovery by the plants was higher with MES) suggests that much more S losses occurred with AS than MES, possibly through S leaching losses. Several studies have shown that AS, composed of salt, is highly soluble and, thus, a great source of immediately available S. However, in coarse-textured soils, particularly, there is a high risk of having S leaching from AS fertilizer during heavy and/or frequent rainfall events. Since SO_4-S is negatively charged, it does not adsorb onto clay or organic matter

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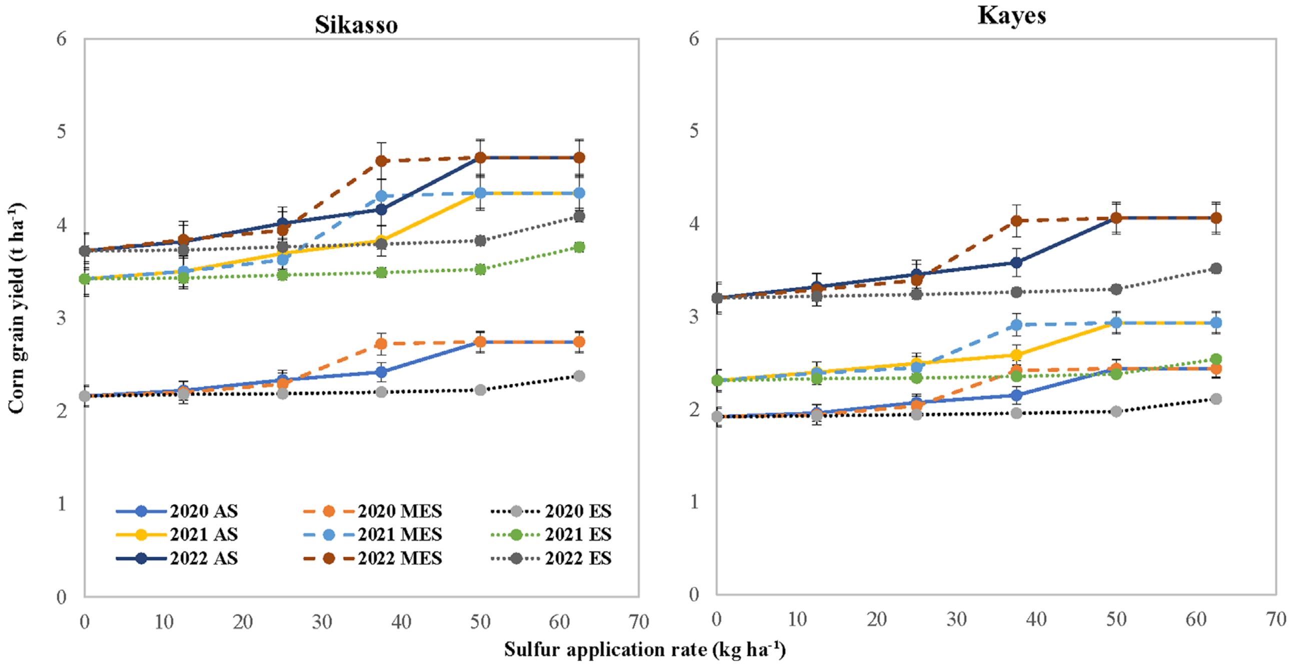

FIGURE 6 Corn grain yield from the Sikasso and Kayes (Mali) sites fertilized with different sulfur sources at different application rates during the 2020–2022 growing seasons. Error bars denote the standard error of the mean. AS, ammonium sulfate; ES, elemental sulfur; MES, micronized elemental sulfur.

TABLE 3 Average apparent sulfur (S) recovery efficiency of corn fertilized with different sources of sulfur applied at different application rates during the 2020–2022 growing seasons.

Location	Application rate (kg S ha^{-1})	AS (%)	MES (%)	ES (%)	Tukey's HSD (0.05)
USA (Milan, TN and Barton, AL)	0	N/A	N/A	N/A	
	12.50	59.7a	59.7a	27.1b	1.98
	18.75	57.9b	59.1a	25.5c	2.42
	25.00	51.5b	54.8a	22.9c	2.28
	31.25	44.3b	48.9a	22.3c	2.75
	Mean	53.4b	55.6a	24.5c	2.14
Ghana (Gushiegu and Karaga)	0	N/A	N/A	N/A	
	15.5	62.2a	64.7a	28.3b	2.66
	22.5	57.3b	60.2a	27.3c	2.57
	30.0	49.1b	52.1a	24.0c	2.66
	37.5	38.4b	42.9a	23.7c	2.48
	Mean	51.8b	55.0a	26.5c	2.45
Mali (Sikasso and Kayes)	0	N/A	N/A	N/A	
	25.0	61.4a	63.6a	22.7b	3.01
	37.5	56.0b	58.9a	22.1c	2.69
	50.0	48.4b	53.7a	21.2c	2.91
	62.5	43.4b	47.5a	19.4c	2.83
	Mean	52.3b	55.9a	21.4c	2.76

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: AS, ammonium sulfate; ES, elemental sulfur; HSD, honest significant difference; MES, micronized elemental sulfur; N/A, not applicable.

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TABLE 4 Average residual soil sulfate-S concentrations measured at the end of each growing season for the duration of the study (2020–2022).

Location	Application rate (kg S ha^{-1})	AS (mg S kg^{-1})	MES (mg S kg^{-1})	ES (mg S kg^{-1})	Tukey's HSD (0.05)
USA (Milan, TN and Barton, AL)	0	1.18a	1.17a	1.15a	0.45
	12.50	1.43a	1.50a	1.52a	0.52
	18.75	1.49b	1.94a	1.55b	0.25
	25.00	1.57b	2.13a	1.63b	0.30
	31.25	1.68b	2.28a	1.57b	0.25
	Mean[a]	1.54b	1.96a	1.57b	0.32
Ghana (Gushiegu and Karaga)	0	1.68a	1.80a	1.57a	0.21
	15.0	1.61b	2.29a	1.43b	0.33
	22.5	1.81b	2.28a	1.46b	0.30
	30.0	1.69b	2.30a	1.63b	0.31
	37.5	1.43b	2.53a	1.78b	0.33
	Mean	1.64b	2.35a	1.58b	0.35
Mali (Sikasso and Kayes)	0	1.24a	1.26a	1.23a	0.25
	25.0	1.33b	1.82a	1.20b	0.26
	37.5	1.50b	2.10a	1.23b	0.30
	50.0	1.54b	2.26a	1.34b	0.35
	62.5	1.59b	2.52a	1.42b	0.34
	Mean	1.49b	2.18a	1.30b	0.29

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: AS, ammonium sulfate; ES, elemental sulfur; HSD, honest significant difference; MES, micronized elemental sulfur; S, sulfur.

[a] Mean represents the average numbers of the treatments receiving sulfur (control values not included).

surfaces and is easily repelled from soils. Thus, with AS, its fast solubility could contribute greatly to SO_4-S losses from the soil. Riley et al. (2002) observed that ≥72% of S contained in applied AS was lost through leaching. Blake-Kalff et al. (2000) reported that most coarse-textured soils have a relatively low sulfate-retention capacity, and even sulfate retained is weakly adsorbed, which can leach with repeated rainfall occurrences. These studies have shown that SO_4-S leaching from the rhizosphere is a crucial phenomenon affecting S availability in agricultural soils. Thus, the timing of sulfate-containing fertilizer application is critical, and in high-rainfall regions, split applications are highly recommended.

4 | SUMMARY AND CONCLUSIONS

The S fertilizer sources significantly affected grain yield, apparent SRE, and apparent S losses at application rates ≥0.75 SR. Across all experimental sites, adding AS and MES to the other limiting non-S nutrient sources resulted in yield increases of up to 28%. Regardless of the location and the growing season, there were no significant differences between MES and AS sources on grain yield at the locally recommended SRs. However, at a lower application of 0.75 SR, grain yields of the MES sources were significantly greater than AS. Across all locations for the three growing seasons, consistently, the lowest grain yield from the S treatments occurred with the ES source, and at S application rates less than SR, grain yield from the ES was not significantly different from the control. Averaged across all locations in the three growing seasons for the AS fertilizer source, applying 50% SR increased corn yield by 8%, relative to the control. Increasing the application rate further to 75% SR, SR, and 125% SR resulted in 12%, 26%, and 28% yield increases, respectively. For the MES-fertilizer product, at 50% SR, the yield increased by up to 6%, and at 75% SR, a yield increase of up to 26% was observed. Further increases in S application rate to SR and 125% SR resulted in marginal increases in yield up to 28%. For the untreated ES, marginal yield increases of up to 10% were observed only when the product was applied at 125% SR. Application of the MES-fertilizer product resulted in the greatest apparent S use efficiency by improving SRE and a consequent reduction of S losses, compared to AS and ES in that order. Thus, with the additional environmental benefits of reduced S losses from the applied fertilizer, we conclude that MES could be an alternate S fertilizer source for profitable and sustainable crop production in S-deficient arable soils. However, economic analysis is needed to determine the potential profitability of utilizing MES-fertilizer products as alternative S sources for crop production; and when the only S

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source available is untreated ES, a relatively high application rate of at least 125% SR should be used.

AUTHOR CONTRIBUTIONS

Cissé Boubakry: Data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Sampson Agyin-Birikorang**: Conceptualization; formal analysis; investigation; methodology; supervision; writing—original draft; writing—review and editing. **Raphael Adu-Gyamfi**: Data curation; project administration; resources, writing—review and editing. **Rachel A. Chambers**: Data curation; methodology; writing—original draft; writing—review and editing. **Ignatius Tindjina**: Formal analysis; methodology; resources; writing—original draft; writing—review and editing. **Albert B. Angzenaa**: Data curation; formal analysis; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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