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Research Article

Response of Two Rye Wheat Varieties to Sulfur Application under Saline–Arid Soil Conditions

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ABSTRACT

Rye wheat productivity can be constrained by inadequate nutrient availability, particularly under challenging soil conditions. This study assessed the effects of agricultural sulfur application on growth and yield-related traits of two rye wheat varieties (Farah and Amal 7). Significant varietal differences were observed for plant height, flag leaf area, fertile spikes, grains per spike, and grain yield. Variety, Farah, produced greater plant height (112.32 cm), whereas variety Amal 7 exhibited larger flag leaf area (29.55 cm^2), more fertile spikes (394.58 spikes m^{-2}), more grains per spike (44.59), and higher grain yield (3.876 t/ha) than Farah (3.606 t/ha). Sulfur application significantly improved most growth and yield attributes. The highest sulfur level (S3 = 1500 kg/ha) produced the greatest plant height (117.13 cm), fertile spike number (405.67 spikes m^{-2}), grains per spike (47.68), and biological yield (12.311 t/ha), while S2 (1000 kg/ha) produced the largest flag leaf area (31.35 cm^2), 1000-grain weight (42.62 g), and a high grain yield (4.072 t/ha). The highest grain yield of 4.148 t/ha was recorded under S3, compared with 3.260 t/ha in the sulfur-free control. Variety × sulfur interactions were significant for flag leaf area and fertile spike number but not for plant height, grains per spike, 1000-grain weight, grain yield, or biological yield. Overall, agricultural sulfur application substantially enhanced rye wheat growth, yield components, and productivity, with S2 and S3 providing the most favorable responses.

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Introduction

The triticale, or rye wheat (*Secale cereale* × *Triticum aestivum*), is an interspecific hybrid, an amphiploid cereal crop that was produced through interspecific hybridization between wheat (*Triticum* spp.) and rye (*Secale cereale* L.). It was originally bred to integrate the best attributes of wheat such as grain quality, higher yield, and adaptability with the disease resistance, high stress tolerance, and ecological resilience of rye. Triticale, due to its typical genetic composition, has been found to perform better under marginal environments such as nutrient-deficient, drought-affected, and saline soils where wheat production is limited (Mergoum et al., 2019; Norboyeva, 2026). The crop is generally characterized by higher vegetative growth, increased plant height, greater biomass production, broadened leaf area and improved tillering ability which are responsible for better resource capture and yield stability (Kumar et al., 2022). Furthermore, triticale grain is comparatively high in protein (around 13-17%) when compared to numerous commonly cultivated wheat cultivars making it suitable for food, feed and industrial usage. Triticale flour can be used for bread making, either alone or in combination with wheat flour to enhance nutritional and functional properties of bread (McGoverin et al., 2020).

Triticale is grown on about 4 million ha worldwide, mainly in areas with temperate climate and difficult growing conditions (FAOSTAT, 2023). It has become even more important as an alternative cereal crop in sustainable agriculture due to its wide adaptability and relatively high productivity under abiotic stresses. Triticale production, however, is still limited in areas like Iraq where soil constraints such as salinity and alkalinity are widely prevalent. Excessive accumulation of soluble salts, low soil nutrient availability, high pH levels and poor soil structures are considered as major constraints affecting plant growth and crop productivity in agricultural soils of Iraq (Al-Rawi and Al-Khafaji, 2023; Walche et al., 2024). In saline and alkaline soils, the availability of vital nutrients, such as phosphorus (P), nitrogen (N), zinc (Zn), iron (Fe), and sulfur (S) is limited as a result of their fixation, precipitation and restrictions in root uptake processes (Rengasamy, 2016; Shahid et al., 2021). Therefore, improvement in chemical properties of soil and enhanced availability of nutrients are important measures to boost productivity of cereals in salt stressed areas.

Sulfur is a vital macronutrient that is required in a variety of physiological and biochemical pathways such as the activation of enzymes, production of chlorophyll, synthesis of proteins and antioxidant defense mechanisms. Elemental sulfur, besides being a plant nutrient, has also been extensively applied as a good soil amendment for the reclamation of alkaline and saline soils. The use of agricultural sulfur acidifies the soil by microbial oxidation of sulfur to sulfuric acid, thus lowering soil pH and increasing the availability and solubility of poorly accessible soil nutrients, such as P, Fe, Mn and Zn (Germida and Janzen, 1993; Kacar and Katkat, 2022). The increased availability of S also improves N use efficiency by enabling the synthesis of amino acids and proteins and thus helping to increase plant growth and grain quality (Droux, 2022).

Moreover, the application of sulfur to saline soils can help improve its properties by releasing calcium from calcium carbonate compounds that will result in the displacement of sodium ions from soil exchange sites and increase salt leaching outside of the root zone. These processes increase permeability of soil, decrease toxic effects of sodium and provide conducive soil rhizosphere conditions for better plant growth (Qadir et al., 2021; Zaman et al., 2023). Hence, soil amelioration through sulfur application is a potential strategy for lucrative and sustainable cultivation of cereal crops in salt affected soils. The efficacy of sulfur application is, however, dependent on soil properties, crop genotype and environmental factors which necessitate the assessment of genotype-specific responses to sulfur fertilization.

With the rapidly growing problems of soil salinity, soil nutrient deficiency and climate change, it is crucial to identify high-performing triticale genotypes and optimize strategies for the management of sulfur for enhancing production of cereals in marginal habitats. Based on this, the present study was carried out to compare the performance of two rye wheat (triticale) varieties (Farah and Amal 7) under different rates of agricultural sulfur application and to find out the optimal rate of sulfur application for the improvement of growth, yield related traits and overall productivity under saline–alkaline soil conditions.

Materials and Methods

Experimental Site

A field experiment was carried out in Samawah district of Al-Muthanna Governorate, Iraq (31.3188° N, 45.2806° E) during the winter growing sowing of 2025–2026. The experimental site had an arid climate characterized by low annual precipitation and high evapotranspiration. The soils of the site were mostly saline–alkaline that adversely limit sustainable cereal cultivation, production potential, and yield performance. The environmental conditions were suitable for assessing the efficacy of sulfur application for enhancing the performance of rye wheat under salt-stressed soils.

Prior to the establishment of the experiment, composite samples of soil (0–30 cm deep) were taken from the experimental site and analyzed for selected physicochemical properties using standard protocols. The soil samples were analyzed at the Al-Amin Foundation for Research and Studies, Holy Shrine of Imam Ali. The analyzed soil properties are shown in Table 1.

Experimental design and treatments

The experiment was designed in two factor factorial in randomized complete block design (RCBD) replicated three times.

The first factor comprised two rye wheat (× Triticosecale Wittmack) varieties:
V1 = Farah
V2 = Amal 7
The second factor consisted of four levels of agricultural sulfur added to the soil:
S0 = 0 kg S ha^{-1} (control),
S1 = 500 kg S $ha^{-1,}$
S2 = 1000 kg S ha^{-1} and
S3 = 1500 kg S ha^{-1}
There were 24 experimental plots consisting of 8 treatment combinations of two varieties and four sulfur levels which were randomly assigned within each block.

Table 1. Physicochemical properties of the experimental soil before sowing.

Characteristic		Unit	Value
pH		-	7.50
E.C (1:1)		dSc.m^{-1}	2.00
Available nitrogen N		mg kg^{-1} soil	57.00
Available phosphorus P			14.00
Available potassium K			152.00
Organic matter (OM)		gm kg^{-1} soil	0.92
Soil parameters	Clay	%	21.00
	Silt		62.00
	Sand		17.00
Soil Texture		Silty clay	

Crop establishment and field management

Conventional tillage was used to prepare the experimental field. The soil was first plowed using a moldboard plow, then harrowed, leveled and graded to prepare a uniform seedbed.

The experimental plots were 2 m × 2 m (4 m^2) in size. Between adjacent plots, a spacing of 1 m and between blocks, a spacing of 2 m was maintained in order to minimalize border effects and facilitate agronomic practices. Prior to sowing, sulfur was applied at uniform application levels into the top 10–15 cm of soil in accordance with the treatment rates. Seeds of both the varieties of rye wheat were planted by hands into 2 m long rows maintaining a row × row distance of 20 cm on 1st November, 2025.

All the agronomic practices such as fertilization, irrigation, weeding, and plant protection measures, were uniformly applied to all the experimental units as per the local guidelines for rye wheat production technology throughout the growing season. Except for sulfur application, all other management practices were the same among treatments.

Measurements of growth and yield attributes

Plant growth and yield parameters were recorded from representative plants from each experimental plot at physiological maturity. Data were recorded for the following parameters:

1. Plant height (cm),
2. Flag leaf area (cm^2),
3. Number of fertile spikes (spikes m^{-2}),
4. Number of grains per spike,
5. Thousand-grain weight (g),
6. Grain yield (t ha^{-1}) and
7. Biological yield (t ha^{-1})

Heights of the plants were measured from the soil surface to the tip of the spike (excluding awns). The flag leaf area was estimated following the standard leaf area estimation methods. Grain and biological yields were measured following harvesting the central rows of each experimental unit and expressed in tons per hectare. The grain samples were cleaned and dried, and then 1000-grain weight was determined from random samples.

Statistical analysis

All the experimental data were analyzed by the analysis of variance (ANOVA) using Genstat statistical computer program to assess the main effects of rye wheat variety, sulfur application rates and their interactions.

The differences among treatment means were tested by Least Significant Difference (LSD) test at 5% probability level ($P \leq 0.05$) as described by Al-Rawi and Khalaf Allah (2000). The data were checked to make sure that it complied with the assumptions of ANOVA (normality of residuals and homogeneity of variance) before analysis.

Results and Discussion

Plant height (cm)

Table 2 shows significant differences ($P \leq 0.05$) in plant height between the two rye wheat varieties and among the agricultural sulfur levels. However, the variety × sulfur interaction did not significantly affect plant height. Variety, Farah, showed greater plant height, with a mean of 112.32 cm, compared with 108.87 cm for Amal 7. The superior plant height of Farah may be associated with genotypic differences in plant architecture and growth potential. These findings are consistent with those of Abd (2025), who reported that genetic factors play an important role in determining plant height in cereal crops.

Table 2. Effect of agricultural sulfur levels on plant height (cm) of two rye wheat (triticale) varieties.

Varieties	Sulfur				Mean
	S0	S1	S2	S3	
Farah	108.47	106.13	117.33	117.33	112.32
Amal 7	101.03	106.26	111.23	116.93	108.87
Mean	104.75	106.20	114.28	117.13	
$L.S.D_{0.05}$	Sulfur		Varieties		Interaction
	4.157		2.939		N.S

Agricultural sulfur application also significantly affected plant height. The highest sulfur level (S3) produced the greatest mean plant height (117.13 cm), whereas the control treatment (S0, without sulfur application) produced the lowest value (104.75 cm). The increase in plant height with sulfur application might be related to the role of sulfur in improving nutrient availability and uptake, thereby promoting vegetative growth and biomass accumulation. Sulfur is also an essential component of sulfur-containing amino acids and several metabolic compounds involved in plant growth and development. The present findings are consistent with those of Marai (2025), who reported that the application of agricultural sulfur enhanced the availability of essential nutrients in the soil and consequently improved vegetative growth.

Despite the significant main effects of variety and sulfur level, no significant differences were observed among the variety × sulfur interaction treatments for plant height, indicating that the response of the two varieties to sulfur application was statistically comparable under the experimental conditions.

Flag leaf area (cm^2)

Significant differences ($P \leq 0.05$) were observed between the rye wheat varieties in flag leaf area as shown in Table 3. Variety 'Amal 7' produced the largest flag leaf area of 29.55 cm^2, while 'Farah' recorded the smallest area (27.92 cm^2). The observed varietal differences may reflect genetic variation in leaf development and assimilatory capacity. Similar differences among rye wheat varieties in flag leaf area have been reported by Al-Badry and Al-Taher (2025).

Agricultural sulfur application also significantly ($P \leq 0.05$) affected flag leaf area. The S2 treatment produced the largest flag leaf area (31.35 cm^2), although this value did not differ significantly from that obtained with S3 (30.05 cm^2). In contrast, the control treatment (S0) resulted in the smallest flag leaf area (24.36 cm^2). The positive response of flag leaf development to sulfur application might be associated with improved nutrient availability and enhanced photosynthetic activity. Because the flag leaf is an important source of assimilates during grain filling, an increase in its area may contribute to greater assimilate production and subsequent grain development. These findings are consistent with Marai (2025), who reported that agricultural sulfur application enhanced vegetative growth and increased leaf area.

Table 3. Effect of agricultural sulfur levels on flag leaf area (cm^2) of two rye wheat varieties.

Varieties	Sulfur				Mean
	S0	S1	S2	S3	
Farah	22.30	28.50	31.63	29.24	27.92
Amal 7	26.43	29.85	31.06	30.85	29.55
Mean	24.36	29.18	31.35	30.05	
$L.S.D_{0.05}$	Sulfur		Varieties		Interaction
	1.527		1.080		2.159

A significant variety × sulfur interaction ($P \leq 0.05$) was also observed for flag leaf area. The V1 × S2 treatment produced the largest flag leaf area (31.63 cm^2), while V1 × S0 produced the smallest (22.30 cm^2). This interaction indicates that the magnitude of the response to sulfur application varied according to genotype.

Number of fertile spikes (spikes m^{-2})

Table 4 demonstrates significant differences ($P \leq 0.05$) between the two varieties regarding the number of fertile spikes. Variety 'Amal 7' produced significantly more fertile spikes (394.58 spikes m^{-2}) than 'Farah' (381.00 spikes m^{-2}). The difference between varieties may be attributable to genetic variation in tillering capacity, spike development, and the ability to retain reproductive tillers under the prevailing environmental conditions. Similar varietal differences in fertile spike production have been reported by Noaema et al. (2020).

The number of fertile spikes also increased significantly ($P \leq 0.05$) with increasing agricultural sulfur application. The highest value was recorded under S3 (405.67 spikes m^{-2}), which did not differ significantly from S2 (400.83

spikes m^{-2}). In contrast, the control treatment (S0) produced the lowest number of fertile spikes (357.50 spikes m^{-2}). The increase in fertile spike number following sulfur application might be associated with improved nutrient availability and uptake, particularly of nitrogen and phosphorus, together with enhanced physiological activity during vegetative and reproductive development. Sulfur is closely involved in nitrogen metabolism and protein synthesis, and an adequate sulfur supply may therefore improve nutrient-use efficiency and reproductive development. These findings are consistent with those reported by Marai (2025).

Table 4. Effect of agricultural sulfur levels on number of fertile spikes (spikes m^{-2}) of two rye wheat varieties.

Varieties	Sulfur				Mean
	S0	S1	S2	S3	
Farah	362.33	389.00	380.67	392.00	381.00
Amal 7	352.67	385.33	421.00	419.33	394.58
Mean	357.50	387.17	400.83	405.67	
$L.S.D_{0.05}$	Sulfur		Varieties		Interaction
	18.390		13.004		26.007

The variety × sulfur interaction was also significant (P ≤ 0.05). The V2 × S2 treatment produced the highest number of fertile spikes (421.00 spikes m^{-2}), whereas V2 × S0 produced the lowest (352.67 spikes m^{-2}). This response suggests that genotype-specific differences in sulfur utilization may influence reproductive development and spike production.

Number of grains per spike (grains spike^{-1})

The analysis of variance showed that variety and agricultural sulfur application had significant effects (P ≤ 0.05) on number of grains per spike (Table 5) while variety × agricultural sulfur application was not significant. The highest mean grains per spike (44.59) were recorded in variety 'Amal 7' and the lowest (41.27 grains per spike) was recorded in variety 'Farah'. The higher number of grains in 'Amal 7' might be due to its higher heritable ability for grain production and/or the ability to make better use of the available environmental resources. The increased photosynthetic efficiency and partitioning of assimilates during spike development might also have accounted for the increased grain set. These results are in line with those reported by Mahdi et al., (2025).

The rate of application of agricultural sulfur had a significant effect (P ≤ 0.05) on the number of grains per spike. S3 application gave the highest value of 47.68 grains per spike but it was not significantly different from S2 (45.78 grains per spike). The lowest value of 36.93 grains per spike was recorded for control treatment (S0). The ameliorative effects of sulfur on the crop might be linked to enhanced availability and uptake of soil nutrients, minerals and water from the soil, improved N metabolism, production of proteins and better nutritional status of plants during reproductive growth. These effects can eventually lead to a decrease in floret abortion and an increase in successful grain set. Marai (2025) also reported similar effects of sulfur application on yield parameters of crops.

The variety × sulfur interaction was not significant, suggesting that the impact of sulfur on number of grains per spike had a similar effect across the two varieties.

Table 5. Effect of agricultural sulfur levels on number of grains per spike (grains spike^{-1}) of two rye wheat varieties.

Varieties	Sulfur				Mean
	S0	S1	S2	S3	
Farah	35.60	38.80	43.70	47.00	41.27
Amal 7	38.27	43.87	47.87	48.37	44.59
Mean	36.93	41.33	45.78	47.68	
$L.S.D_{0.05}$	Sulfur		Varieties		Interaction
	4.690		3.316		N.S

1000-grain weight (g)

The effect of the application of agricultural sulfur on 1000-grain weight was significant (P ≤ 0.05) as presented in Table 6. The mean 1000-grain weight of S2 treatment was the highest (42.62 g), but not significantly different from the S3 and S1 treatments (42.04 g and 40.87 g respectively). The control treatment (S0) resulted in the lowest 1000-grain weight of 36.02 g. The higher grain weight following sulfur application might be related to the better nutritional status of the plants, and better nitrogen and phosphorus use efficiency. Sufficient availability of sulfur is crucial for the synthesis of amino acids and proteins and might contribute to accumulation of assimilates in developing grains, which in turn can lead to improved grain size and weight.

There were no significant differences for 1000-grain weight between the varieties or among the variety ×

sulfur interaction treatments. This indicates that grain weight responded more to sulfur availability than to varietal differences.

Table 6. Effect of agricultural sulfur levels on 1000-grain weight (g) of two rye wheat varieties.

Varieties	Sulfur				Mean
	S0	S1	S2	S3	
Farah	37.70	41.90	42.43	42.70	41.18
Amal 7	34.33	39.83	42.81	41.38	39.59
Mean	36.02	40.87	42.62	42.04	
L.S.D$_{0.05}$	Sulfur		Varieties		Interaction
	3.907		N.S		N.S

Grain yield (t/ha)

Grain yield was significantly different among varieties and agricultural sulfur rates as shown in table 7; however, there were no significant differences among their interactions. The grain yields in case of 'Amal 7' were significantly higher than 'Farah' with a mean of 3.876 t/ha and 3.606 t/ha respectively. The increased yield of 'Amal 7' might be related to its better performance in yield components such as numbers of fertile spikes and grains per spike. These results further highlight the role of genetic variability in determining grain productivity, and the need to choose high-yielding varieties that are best suited to the local environments. Leiby et al. (2025) also found similar varietal differences in grain yield.

Table 7. Effect of agricultural sulfur levels on grain yield (t/ha) of two rye wheat varieties.

Varieties	Sulfur				Mean
	S0	S1	S2	S3	
Farah	3.103	3.343	3.897	4.080	3.606
Amal 7	3.417	3.623	4.247	4.217	3.876
Mean	3.260	3.483	4.072	4.148	
L.S.D$_{0.05}$	Sulfur		Varieties		Interaction
	0.3095		0.2189		N.S

Grain yield was significantly higher ($P \leq 0.05$) with the application of agricultural sulfur. No significant difference was found between the S3 and S2 treatments which resulted in the highest grain yields of 4.148 and 4.072 t/ha respectively. The control treatment (S0) on the other hand gave the lowest grain yield of 3.260 t/ha. The enhancements in grain yields with S2 and S3 applications might be, in parts, due to better yield attributes such as greater number of fertile spikes, greater number of grains per spike and greater thousand grain weight. This increased sulfur supply can contribute to increased nutrient acquisition, nitrogen metabolism, photosynthetic activity and partitioning of assimilates that favor reproductive growth and formation of grains.

The interaction between varieties and sulfur applications was not found significant regarding grain yield suggesting that the positive response of sulfur application on grain yield was not greatly influenced by variety.

Biological yield (t ha^{-1})

The biological yield was significantly ($P \leq 0.05$) affected by agricultural sulfur rates. On the other hand, the effect of varieties and the variety × sulfur interaction did not significantly affect the biological yield as shown in Table 8. The highest biological yield of 12.311 t/ha was obtained with the S3 treatment whereas the lowest value (9.568 t/ha) was recorded from the control treatment (S0).

Table 8. Effect of agricultural sulfur levels on biological yield (t ha^{-1}) of two rye wheat varieties.

Varieties	Sulfur				Mean
	S0	S1	S2	S3	
Farah	9.147	10.633	11.125	12.083	10.747
Amal 7	9.988	11.162	11.800	12.538	11.372
Mean	9.568	10.898	11.463	12.311	
L.S.D$_{0.05}$	Sulfur		Varieties		Interaction
	0.9618		N.S		N.S

The higher biological yield with S3 application could be linked to better vegetative growth, measured in terms of plant height, increased production of fertile spikes as well as grain yield. Proper application of sulfur nutrition can enhance nutrient use efficiency and facilitate protein production and other metabolic activities needed for biomass buildup. Therefore, the increased biological production with sulfur application might be due to the overall betterment in crop growth and production.

The interaction between varieties and the variety × sulfur interaction treatments did not significantly differ in the case of biological yield.

Conclusions

The results of the present study show that under the current experimental conditions, both the varieties (Farah and Amal 7) and the application of agricultural sulfur has significant effect on the growth, yield parameters and productivity of rye wheat. Under the prevailing environmental conditions, Variety 'Amal 7' performed better than the variety 'Farah' in terms of flag leaf area, number of fertile spikes, number of grains per spike and grain yield, suggesting its higher yield potential. Farah, on the other hand, yielded higher plant height indicating that varietal supremacy may differ among individual agronomic characters.

Application of agricultural sulfur especially S3 (1500 kg S ha-1) significantly enhanced various agronomic and yield attributes such as plant height, number of fertile spikes, number of grains per spike, grain yield, and biological yield. The S2 (1000 kg S ha-1) treatment also showed good results for other characteristics, such as flag leaf area and 1000-grain weight. The significant varietal × sulfur interaction for flag leaf area and number of fertile spikes also suggests that responses of varieties to sulfur application can differ for particular growth and yield parameters.

The overall results indicate that application of agricultural sulfur as soil amendments could be an important strategy to enhance rye wheat productivity under arid and potentially nutrient-deficient environments. Nonetheless, the sulfur rate needs to be standardized for optimal application depending upon type of cultivar, edaphic factors, and environmental conditions to maximize agronomic efficiency and avoid unnecessary input. Additional multi-location and multi-season trials are suggested to confirm these results and to select stable and high performing rye wheat varieties for the arid and saline–arid environments.

Author Contributions

HRL and HAAI conceptualized and designed the study. HRL conducted the field investigations and performed the experimental work. ASF provided overall supervision and ensured methodological rigor and analytical consistency throughout the study. AHK and SHH served as co-supervisors, providing critical guidance on experimental design, data interpretation, and scientific refinement at various stages of the research. HRL, HAAI, NHM, and AHK contributed to the preparation of the initial manuscript, including content organization, compilation of results, and integration of preliminary interpretations. All authors subsequently critically reviewed and revised the manuscript, contributed to its intellectual refinement, verified the data and analyses, and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger

SDG 12: Responsible Consumption and Production

SDG 15: Life on Land

Policy Addressed

Sustainable soil management, salinity management and reclamation, and climate-smart agriculture policies should promote sulfur-based soil amelioration, salt-tolerant varieties, efficient nutrient and water management, and site-specific practices to enhance cereal productivity and resilience in saline–arid environments.

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