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Impacts of Sulfur-nitrogen Interaction on Soil Saline-alkaline Properties and Yield of Sunflower Field in Hetao Irrigation District

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Abstract

The interaction between elemental sulfur (S^0) and nitrogen (N) element exceeds the sum of their separate effects. In this study, we evaluated the impacts of the interaction of S^0 and different N fertilization rates on the soil saline-alkaline properties and yield of sunflower field in Hetao Irrigation District (HID) by conducting a randomized block field experiment. The experimental treatment included 4 levels [N0 (no N fertilizer), N1 (35 kg urea/667m^2), N2 (26.25 kg urea/667m^2), N3 (17.5 kg urea/667m^2)], 6 replicates. No S^0 was applied in 2020 and S^0 in 2021. The data showed that the S^0 significantly reduced the pH values at the 0-20 and 20-40 cm depths by 0.36 and 0.31, respectively, and reduced the soil exchangeable sodium percentage, exchangeable sodium, and cation exchange capacity. The S^0 can maximize the yield at the N3 among the 4 levels of N fertilization rates. These findings indicated that the sulfur-nitrogen interaction can improve the alkaline soil and reduce the N fertilization rate for the sunflower in the HID.

Keywords

Sulfur-nitrogen interaction; Sunflower; Soil saline-alkaline properties; Yield; Hetao Irrigation District

The Hetao Irrigation District belongs to Bayannur City, Inner Mongolia, with a total cultivated land area of about 10.2 million mu (Ordos New Media Center, 2019). Due to the arid climate, high groundwater level and large evaporation in the district, its agricultural soil has interannual periodic secondary salinization (Sang, 1996). Sunflower (*Helianthus annuus* L.) has become the dominant crop in the irrigation district adapted to saline-alkali land in the past 50 years due to its salt tolerance, accounting for about 39% of the cultivated land area of the entire irrigation district and one-quarter of the national area (Gao, Gao, & Yang, 2019). According to statistics, between 2000 and 2018, the average yield of sunflowers in Inner Mongolia was about 158 kg/ 667 m2, with a low overall yield, and the yield has been declining since 2013 (Inner Mongolia Bureau of Statistics, 2019). However, the amount of chemical fertilizer applied remains high (Lai, Meili, & Yang, 2022). The average pH value of the agricultural soil in the district is >8.0 and has an increasing trend (Lai, Meili, & Yang, 2022). When the pH value is greater than 8, nitrogen nitrification is inhibited, and the conversion of nitrogen fertilizer into available nitrogen is reduced (McCauley, Jones, & Jacobsen, 2003). It is necessary to increase the amount of nitrogen fertilizer to meet the needs of crops for nitrogen, which leads to an increase in the amount of nitrogen applied. High nitrogen application can easily lead to nitrogen loss, which in turn pollutes local water resources, consumes the ozone layer in the Earth's atmosphere, and causes

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global warming (Lai et al., 2018). Therefore, how to reduce nitrogen application while increasing sunflower yield has become a real need for agricultural production in the Hetao Irrigation District.

Elemental sulfur (SO) is difficult to dissolve in water and is slowly oxidized by microorganisms to lower the pH of alkaline soils (Cao, Meng, & Hu, 2011). Lowering the pH of alkaline soils (from > 8 to 7) can increase the availability of macro- and micronutrients such as nitrogen and phosphorus in the soil (McCauley, Jones, & Jacobsen, 2003; Cao, Meng, & Hu, 2011) and to some extent affect the diversity and enzyme activity of soil microorganisms (Pietri & Brookes, 2008; Zheng, 2012). The main processes of nitrogen transformation in soil include nitrogen fixation, ammonification, nitrification and denitrification, all of which are driven by microorganisms (He & Zhang, 2013). These suggest that the interaction between sulfur and nitrogen and its effects are greater than its nutritional role alone (Cao, Meng, & Hu, 2011). However, in the Hetao irrigation area, research on the effects of the interaction between elemental sulfur and nitrogen fertilizer on soil salinity and yield has been lacking.

Therefore, this study evaluated the effects of the interaction between S0 and different nitrogen application rates on soil salinity and alkalinity indicators (pH value, alkalinity, electrical conductivity, sulfate ions, exchangeable sodium, cation exchange capacity) and yield through field experiments, providing a new approach and basis for improving saline-alkali land and reducing nitrogen fertilizer application in the Hetao Irrigation District.

1. Materials and Methods

1.1 Overview of the Study Area

The experimental field is located in Fuxing Town, Wuyuan County, Bayannur City, Inner Mongolia Autonomous Region (107°56'38.630"). E, 40°57'0.288" N; Altitude: 1031.11 m. This area has a mid-latitude continental climate, characterized by dryness and sparse rainfall; the annual precipitation from 1982 to 2021 was 180.59 mm. mm and mostly concentrated in summer and autumn, with an average annual temperature of 8.99°C (WheatA, 2021). The soil in the experimental site is alluvial soil with a texture of silty clay loam (20.8% sand, 61.3% silt, and 17.9% clay). Initial data showed that the soil pH in the 0~20 cm depth was 8.12, alkalinity was 30.61%, electrical conductivity was 1.01 mS /cm, organic matter was 11.9 g/kg, total nitrogen was 0.83 g/kg, nitrate nitrogen was 5.65 mg/kg, available phosphorus was 29.22 mg/kg, and available potassium was 309.18 mg/kg.

1.2 Experimental Design

The 2020 experiment was a single-factor (nitrogen application rate) randomized block design with 6 replicates and a total of 24 plots, each with an area of 88.58 m². Nitrogen application rate (46% N urea, topdressing applied in holes on July 19th) included four levels: N0 (no nitrogen fertilizer, CK); N1 (conventional nitrogen fertilizer application rate) 35 kg urea/ 667 m²; N2 (75% of N1) 26.25 kg urea/ 667 m²; N3 (50% of N1) 17.5 kg urea/ 667 m². The tested crop was sunflower (variety: Sanrui 361). On May 24th, 40 kg / 667 m² of superphosphate (46% P_2O_5) was applied as basal fertilizer via machine, followed by mulching (partial mulching). Spring irrigation, i.e., flooding with water from the Yellow River, will be carried out on May 26. Sowing will begin on June 8, and harvesting will take place on October 2. Other farmland management methods will be the same as usual.

The 2021 trial involved applying elemental sulfur fertilizer to the same experimental plots as in 2020. Specifically, each plot received the same amount of elemental sulfur fertilizer (90 % S0) (pure amount of 8.4 kg S0 / 667 m²). Sowing took place on June 5th, and harvesting on October 1st. Other management practices remained the same as in 2020.

1.3 Soil Sample Collection and Laboratory Testing

22, 2020, the second on October 2, 2020, and the third on October 4, 2021. For each experimental plot, one composite sample was collected using a soil auger each time. This composite sample consisted of four randomly collected samples (two from the covered area and two from the uncovered area), taken at depths ranging from 0 to 20 mm. cm, 20 ~ 40 A total of 144 mixed samples were collected.

The collected samples were taken to the laboratory to dry, grind, and sieve through a 2mm sieve before laboratory testing and analysis of soil pH, alkalinity, conductivity, sulfate ions, exchangeable sodium, and cation exchange capacity. All test methods adopted national standardized methods: LY/ T1251-1999 "Analysis of Water-Soluble Salts in Forest Soils: Determination of Conductivity, Sulfate, etc."; LY / T1239-1999 "Determination of pH in Forest Soils";

NY/ T1121.5-2006 "Soil Testing Part 5: Determination of Cation Exchange Capacity in Calcareous Soils"; LY/ T1248-1999 "Determination of Exchangeable Sodium in Alkaline Soils"; LY/ T1249-1999 "Calculation of Soil Alkalinity".

1.4 Methods for determining sunflower yield

When the sunflowers mature, samples are taken from the middle section (two rows) of each plot. Following the order of the plants in the field, 10 sunflower heads are harvested sequentially. The seeds are then threshed, dried, and the yield is calculated.

1.5 Statistical Analysis

The PROC GLIMMIX method (mixed model method) in SAS 9.4 statistical software was used to compare the differences in soil properties and sunflower yield under different nitrogen application rates. The PROC method in SAS 9.4 was employed. The paired two-sample t-test in TTEST was used to compare the differences in soil properties before and after the sunflower growth period. The significance level was set at α=0.05.

2. Results

There were no significant differences in soil pH values under different nitrogen application rates (Table 1a). In 2020 (without sulfur fertilizer application), there were no significant differences in soil pH values before and after the growth period for sunflowers at a depth of 0–20 cm; however, the pH values at a depth of 20–40 cm showed a statistically significant difference before and after the growth period ($P = 0.02$, but the absolute difference was only 0.05). In 2021 (with sulfur fertilizer application), there were significant differences in mean soil pH values before and after the growth period (the pH difference between 0–20 cm and 20–40 cm depths was 8.08–7.72 = 0.36 and 8.10–7.79 = 0.31, respectively) (Table 2).

There were no significant differences in soil alkalinity under different nitrogen application rates (Table 1a). In 2020, when no sulfur fertilizer was applied, the soil alkalinity before the growing season for sunflowers at depths of 0–20 cm and 20–40 cm (24.68% and 35.93 %, respectively) was significantly lower than after the growing season (39.49 % and 53.61%, respectively). However, in 2021 (when sulfur fertilizer was applied), there were no significant differences in soil alkalinity before and after the growing season (Table 2).

0–20 cm and 20–40 cm depth) under different nitrogen application rates showed no significant difference in 2020. However, in 2021, at a depth of 0–20 cm, the electrical conductivity under N2 conditions (1.17 mS /cm) was significantly higher than that under N0 (0.61 mS / cm); at a depth of 20–40 cm, the electrical conductivity under N1, N2, and N3 conditions was 1.08, 1.23, and 1.04, respectively. The soil electrical conductivity (mS /cm) was significantly higher than that of N0 (0.52 mS /cm) (Table 1a). In 2020, when no sulfur fertilizer was applied, and in 2021, when sulfur fertilizer was applied, there were no significant differences in soil electrical conductivity before and after the growth period of 0–20 cm and 20–40 cm (Table 2).

0-20 cm and 20-40 cm depth) under different nitrogen application rates showed no significant difference in 2020. In 2021, sulfate ion concentrations at a depth of 0–20 cm showed no significant difference under different nitrogen application rates; however, at a depth of 20–40 cm, sulfate ion concentrations at N1, N2, and N3 levels were significantly higher (0.86, 1.00, 1.02 ... Sulfate ions (mg/kg) were significantly higher than N0 (0.30 mg/kg) (Table 1b). In 2020, when no sulfur fertilizer was applied, soil samples taken before the growing season were unavailable for testing sulfate ion content. In 2021, when sulfur fertilizer was applied, there was no significant difference in soil sulfate ions before and after the growing season for sunflowers at a depth of 0–20 cm. However, sulfate ions at a depth of 20–40 cm before the growing season (1.17 mg/kg) were significantly higher than those after the growing season (0.80 mg/kg) (Table 2).

significant differences in soil exchangeable sodium under different nitrogen application rates (Table 1b). In 2020, without sulfur fertilizer application, the soil exchangeable sodium before the growth stage of sunflowers at depths of 0–20 cm and 20–40 cm (3.23 and 4.24 cmol (+)/kg) was significantly lower than after the growth stage (5.45 and 7.00 cmol (+)/kg). However, in 2021 (with sulfur fertilizer application), there were no significant differences in soil exchangeable sodium before and after the growth stage at depths of 0–20 cm and 20–40 cm (Table 2).

Table 1a. Mean values of soil pH, alkalinity, and electrical conductivity under different nitrogen application rates in 2020 (without sulfur fertilizer) and 2021 (with sulfur fertilizer)

deal with	pH		Soil alkalinity		electrical conductivity	
	2020	2021	2020	2021	2020	2021
			%		mS /cm	
			0 ~ 20 cm			
Nitrogen application rate (N) †						
N0	8.07 a ‡	7.78 a	46.37 a	34.05 a	0.98 a	0.61 b
N3	8.06 a	7.698 a	39.52 a	41.05 a	1.05 a	0.97 ab
N2	8.11 a	7.702 a	34.55 a	41.36 a	0.86 a	1.17 a
N1	8.08 a	7.687 a	37.52 a	36.09 a	1.05 a	0.85 ab
			Analysis of variance (P>F)			
N	0.89	0.49	0.09	0.57	0.72	0.01
			20 ~ 40 cm			
Nitrogen application rate (N)						
N0	8.11 a	7.82 a	59.36 a	49.08 a	1.11 a	0.52 b
N3	8.097 a	7.79 a	43.48 a	53.98 a	1.26 a	1.04 a
N2	8.093 a	7.78 a	60.86 a	54.07 a	1.16 a	1.23 a
N1	8.095 a	7.76 a	50.75 a	50.91 a	0.98 a	1.08 a
			Analysis of variance (P>F)			
N	0.99	0.3	0.053	0.68	0.34	0.004

Note: † N0 = 0 (no nitrogen fertilizer applied); N1 = 35 kg urea/ 667 m^2 (conventional nitrogen fertilizer application rate); N2 = 26.25 kg urea/ 667 m^2 (75% of N1); N3 = 17.5 kg urea/ 667 m^2 (50% of N1). † Different lowercase letters indicate significant differences between different levels within the same treatment (α = 0.05).

Table 1b. Mean values of soil sulfate ions, exchangeable sodium, and cation exchange capacity under different nitrogen application rates in 2020 (without sulfur fertilizer) and 2021 (with sulfur fertilizer)

deal with	sulfate ions		exchangeable sodium		Cation exchange capacity	
	2020	2021	2020	2021	2020	2021
	mg/kg			cmol (+)/kg		
			0 ~ 20 cm			
Nitrogen application rate (N) †						
N0	0.95 a ‡	0.71 a	6.06 a	4.41 a	13.11 b	13.02 a
N3	0.76 a	0.83 a	5.46 a	5.48 a	13.85 ab	13.41 a
N2	1.02 a	0.79 a	4.88 a	5.64 a	14.19 ab	13.77 a
N1	0.72 a	0.85 a	5.39 a	4.76 a	14.50 a	13.17 a
			Analysis of variance (P>F)			
N	0.12	0.90	0.31	0.38	0.04	0.37
			20 ~ 40 cm			
Nitrogen application rate (N)						
N0	0.94 a	0.30 b	7.87 a	6.11 a	13.27 a	12.47 a
N3	1.42 a	1.02 a	6.07 a	7.32 a	14.15 a	13.45 a
N2	1.12 a	1.00 a	7.82 a	6.75 a	13.32 a	12.29 a
N1	1.20 a	0.86 a	6.22 a	6.67 a	12.27 a	13.21 a
			Analysis of variance (P>F)			
N	0.103	＜0.001	0.08	0.65	0.42	0.60

Note: † N0 = 0 (no nitrogen fertilizer applied); N1 = 35 kg urea/ 667 m^2 (conventional nitrogen fertilizer application rate); N2 = 26.25 kg urea/ 667 m^2 (75% of N1); N3 = 17.5 kg urea/ 667 m^2 (50% of N1). † Different lowercase letters indicate significant differences between different levels within the same treatment (α = 0.05).

Table 1c. Mean values of soil pH, alkalinity, and electrical conductivity before and after the sunflower growing season in 2020 (without sulfur fertilizer) and 2021 (with sulfur fertilizer)

years	pH	Soil alkalinity	electrical conductivity	sulfate ions	exchangeable sodium	Cation exchange capacity
		%	mS /cm	mg/kg	cmol (+)/kg	
				0~20 cm		
2020						
April 2020	8.076 a †	24.68 b	0.99 a	-	3.23 b	13.06 b
October 2020	8.080 a	39.49 a	0.98 a	0.86	5.45 a	13.91 a
Difference	-0.0046	-14.81	0.01	-	-2.22	-0.85
T- test p- value	0.84	<0.001	0.92	-	<0.001	0.005
2021						
October 2020	8.08 a	39.49 a	0.98 a	0.86 a	5.45 a	13.91 a
October 2021	7.72 b	38.14 a	0.90 a	0.80 a	5.07 a	13.34 b
Difference	0.36	1.35	0.08	0.06	0.38	0.57
T- test p- value	<0.001	0.70	0.40	0.58	0.38	0.01
				20~40 cm		
2020						
April 2020	8.15 a	35.93 b	1.03 a	-	4.24 b	11.63 b
October 2020	8.10 b	53.61 a	1.13 a	1.17	7.00 a	13.25 a
Difference	0.05	-17.68	-0.10	-	-2.76	-1.62
T- test p- value	0.02	<0.001	0.24	-	<0.001	<0.001
2021						
October 2020	8.10 a	53.61 a	1.13 a	1.17 a	7.00 a	13.25 a
October 2021	7.79 b	52.01 a	0.97 a	0.80 b	6.71 a	12.86 a
Difference	0.31	1.60	0.16	0.37	0.29	0.39
T- test p- value	<0.001	0.62	0.07	<0.001	0.47	0.25

Note: † Different lowercase letters indicate significant differences in soil properties before and after the sunflower growth period (α=0.05).

In 2020, the soil cation exchange capacity (CEC) at a depth of 0－20 cm under N1 (14.50 cmol (+) / kg) was significantly higher than that under N0 (13.11 cmol (+)/kg). However, there was no significant difference in CEC under different nitrogen application rates at a depth of 20–40 cm. In 2021, there were no significant differences in CEC under different nitrogen application rates (Table 1b). In 2020, when no sulfur fertilizer was applied, the CEC at depths of 0–20 cm and 20–40 cm before the growing season (13.06 and 11.63 cmol (+)/kg) was significantly lower than that after the growing season (13.91 and 13.26 cmol (+)/kg). However, in 2021, when sulfur fertilizer was applied, the soil cation exchange capacity before the growth period in the 0-20 cm depth (13.91 cmol (+)/kg) was significantly higher than that after the growth period (13.34 cmol (+)/kg); there was no significant difference in soil cation exchange capacity before and after the growth period in the 20-40 cm depth (Table 2).

2020, when no sulfur fertilizer was applied, the sunflower yield under N1 (283.79 kg / 667m2) was significantly higher than that under N3 (250.28 kg/ 667m2) and N0 (221.49 kg/ 667m2); the yield under N2 (259.49 kg / 667m2) was significantly higher than that under N0 (221.49 kg/ 667m2). In 2021, when sulfur fertilizer was applied, there was no significant difference in yield under different nitrogen application rates. The yields under different nitrogen application rates, ranked from highest to lowest, were: N3 (249.01 kg / 667m2) > N0 (246.47 kg / 667m2) > N1 (244.78 kg/ 667m2) > N2 (229.53 kg/ 667m2).

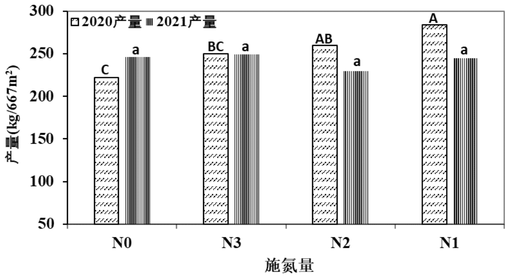

Figure 1. Mean sunflower yield under different nitrogen application rates in 2020 (without sulfur fertilizer) and 2021 (with sulfur fertilizer).

Note: N0 = 0 (no nitrogen fertilizer applied); N1 = 35 kg urea/ 667m 2 (conventional nitrogen fertilizer application rate); N2 = 26.25 kg urea/ 667m 2 (75% of N1); N3 = 17.5 kg urea/ 667m 2 (50% of N1).

3. Discussion

3.1 Effects of Sulfur Fertilizer on Soil Salinity and Alkalinity Characteristics under Different Nitrogen Application Rates

The aforementioned results show that the greatest impact of sulfur fertilizer on soil salinity and alkalinity under different nitrogen application rates is a significant reduction in soil pH (Table 2), which is consistent with previous research findings (McCauley, Jones, & Jacobsen, 2003; Liang, 2017). This is mainly because SO_2 is oxidized by microorganisms to generate sulfate ions (SO_4^{2-}) and hydrogen ions (H^+), thereby reducing soil pH. Since SO_2 is difficult to dissolve in water, the microbial oxidation process is slow (Cao, Meng, & Hu, 2011; Slaton, Norman, & Gilmour, 2001), resulting in a relatively stable reduction in soil pH, which can be maintained for a relatively long time. The reduced soil pH in this study can be maintained for at least one growing season.

2020, when no sulfur fertilizer was applied, the soil alkalinity before the sunflower growing season was significantly lower than after the growing season. However, in 2021, when sulfur fertilizer was applied, there was no significant difference in soil alkalinity before and after the growing season (Table 2). This suggests that elemental sulfur fertilizer can reduce soil alkalinity, which is consistent with previous studies (Liu et al., 2008). The main reason is that as sulfur fertilizer undergoes microbial oxidation, the soil pH decreases, and the poorly soluble calcium carbonate in the soil begins to dissolve and replace some of the exchangeable sodium (which also explains the results of exchangeable sodium in Table 2), thereby reducing soil alkalinity (Liu et al., 2008).

2021, when sulfur fertilizer was applied, high nitrogen application significantly increased soil electrical conductivity (0-20 and 20-40 cm) (Table 1a); high nitrogen application also significantly increased sulfate ions (20-40 cm) (Table 1b). This suggests that sulfur-nitrogen interaction can increase soil salinity, which is consistent with previous research results (Slaton, Norman, & Gilmour, 2001). The main reason is that the increased nitrogen fertilizer can increase nitrate in the soil. Thiobacteria play a major role in the sulfur oxidation process. Among them, deammonium thiobacterium can obtain energy from the oxidation of elemental sulfur to sulfate, and can also use nitrate as an electron donor to obtain energy to oxidize elemental sulfur and catalyze the oxidation reaction of elemental sulfur by other thiobacteria (Cao, Meng, & Hu, 2011). Therefore, the interaction between increased nitrogen fertilizer and elemental sulfur can increase the content of soil sulfate (i.e. sulfate ions), thereby increasing soil electrical conductivity. The sulfate ion concentrations at depths of 20–40 cm in 2021 were significantly higher than those after the growing season (Table 2). This may be because the sulfate produced by sulfur oxidation is more active and is lost to groundwater with precipitation (the rainfall on July 25 and September 3, 2021 was both >15 mm).

2021, when sulfur fertilizer was applied, the soil cation exchange capacity of sunflowers at a depth of 0-20 cm before the growing season was significantly higher than that after the growing season (Table 2). The main reason is that pH value can affect the dissociation of hydroxyl groups (-OH) on the surface of soil colloidal particles. When the pH value decreases (Table 1a), the negative charge on the surface of soil colloidal particles decreases, thus reducing the cation exchange capacity (Zhu, Chen, & Chen, 2019).

3.2 Effects of Sulfur Fertilizer on Sunflower Yield under Different Nitrogen Application Rates

2020, when no sulfur fertilizer was applied, nitrogen application significantly affected sunflower yield, with yields from highest to lowest under different nitrogen application rates ranking as follows: N1 > N2 > N3 > N0 (Figure 1). However, in 2021, when sulfur fertilizer was applied, there was no significant difference in yields under different nitrogen application rates, with yields from highest to lowest ranking as follows: N3 > N0 > N1 > N2 (Figure 1). This suggests that applying elemental sulfur can achieve the maximum yield with a low nitrogen application rate (N3) (in this case, the ratio of pure elemental sulfur fertilizer to pure nitrogen fertilizer is 8.44 kg). S 0 / 6 67m 2 8.05 kg. The concentration of nitrogen (N/ 667m^2) makes it possible to reduce the amount of nitrogen fertilizer applied. Previous studies have shown that, under certain conditions, the combined application of sulfur and nitrogen fertilizers results in higher yields than nitrogen fertilizer alone (Verma wt al., 2018; Liu, Shi, & Gong, 2012). However, when nitrogen fertilizer is insufficient, the application of sulfur fertilizer has a negative impact on the absorption and utilization of nitrogen by crops (Liu, Shi, & Gong, 2012). Therefore, a suitable ratio of available nitrogen and sulfur in the soil is needed to promote nutrient absorption and crop growth. However, the optimal ratio in sunflower field soil is still uncertain and requires further research.

4. Conclusion

Applying elemental sulfur fertilizer to alkaline soils of sunflowers in the Hetao Irrigation District significantly reduces soil pH, and this reduced pH level can be maintained for at least one growing season. It also reduces soil alkalinity, exchangeable sodium, and cation exchange capacity, thus improving alkaline soil conditions. Sulfur-nitrogen interaction increases soil salinity and sulfate ions; however, the increased salinity and sulfate ions can infiltrate into groundwater with precipitation or irrigation water. Applying elemental sulfur fertilizer maximizes yield with low nitrogen application rates, resulting in an optimal pure sulfur-to-nitrogen ratio of 8.44:8.05 (kg/ 667m^2), which significantly reduces nitrogen fertilizer application. Future research will explore the optimal ratio of available sulfur to available nitrogen in sunflower soils in the Hetao Irrigation District and the long-term effects of sulfur-nitrogen interaction on soil properties.

References

Cao, Z., Meng, C., & Hu, Z. (2011). Sulfur in Chinese agriculture and the environment. Science Press.

Gao, J., Gao, X., & Yang, X. (2019, December 17). Hetao Sunflower: I am a shining name card of Bayannur. Bayannur News Network. Retrieved from

He, J., & Zhang, L. (2013). Key microbial processes and mechanisms of nitrogen transformation in soil. *Bulletin of Microbiology*, *40*(1), 98-108.

Inner Mongolia Bureau of Statistics. (2019). Inner Mongolia statistical yearbook 2019. China Statistics Press.

Lai, L., Hong, C. O., Kumar, S., Chintala, R., Sadeghpour, A., & Rice, P. J. (2018). Soil nitrogen dynamics in switchgrass seeded to a marginal cropland in South Dakota. *GCB Bioenergy*, *10*(1), 28-38. https://doi.org/10.1111/gcbb.12443

Lai, L., Meili, & Yang, Y. (2022). Analysis of agricultural soil characteristics and development in the Hetao Irrigation District of Inner Mongolia. *Jiangsu Agricultural Sciences*, *50*(2), 213-218.

Liang, F. (2017). Practical Q&A, technical models, and case studies of integrated water and fertilizer management. China Agriculture Press.

Liu, G., Li, X., Zhang, Y., Zhang, J., & Zhao, M. (2008). A preliminary study on sulfur-based improvement of saline-alkali soil in northern Yinchuan region. *Arid Zone Agricultural Research*, *26*(4), 79-82.

Liu, Y., Shi, H., & Gong, Y. (2012). Effects of combined sulfur and nitrogen application on nitrogen translocation and leaf senescence in green wheat. *Northwest Botanical Journal*, *32*(6), 1206-1213.

McCauley, A., Jones, C., & Jacobsen, J. (2003). Nutrient management module No. 8: Soil pH and organic matter. MSU Extension Service Continuing Education Series, Minnesota State University. Retrieved from

Ordos New Media Center. (2019, November 13). Ordos: Inner Mongolia irrigation structure included in ICID register. China Daily. Retrieved from htm

Pietri, J. C. A., & Brookes, P. C. (2008). Relationships between soil pH and microbial properties in a UK arable soil. *Soil Biology and Biochemistry*, *40*(7), 1856-1861. https://doi.org/10.1016/j.soilbio.2008.03.020

Slaton, N. A., Norman, R. J., & Gilmour, J. T. (2001). Oxidation rates of commercial elemental sulfur products applied to an alkaline silt loam from Arkansas. *Soil Science Society of America Journal*, *65*(1), 239-243. https://doi.org/10.2136/sssaj2001.651239x

Verma, O. P., Singh, S., Pradhan, S., Verma, S. S., & Singh, A. K. (2018). Irrigation, nitrogen and sulfur fertilization response on productivity, water use efficiency and quality of Ethiopian mustard (*Brassica carinata*) in a semi-arid environment. *Journal of Applied and Natural Science*, *10*(2), 593-600. https://doi.org/10.31018/jans.v10i2.1717

WheatA. (2021). Meteorological data (10 km accuracy). (Agricultural Meteorological Big Data System V1.4.5) [Data set]. WheatA Big Data Information (Ningbo) Co., Ltd.

Y. (1996). Causes and characteristics of alkaline soils in the Hetao Irrigation District of Inner Mongolia. *Acta Pedologica Sinica*, *33*(4), 398-404.

Zheng, S. (2012). Effects of sulfur fertilizer on soil properties, heavy metal speciation and crop growth (Doctoral dissertation). Huazhong Agricultural University, Wuhan, China.

Zhu, H., Chen, J., & Chen, S. (2019). Soil geography (3rd ed.). Higher Education Press.