# Effects of Sulfur Fertilizer Rate on Nitrogen and Sulfur Uptake, Distribution, and Yield in Maize (Postprint)

**Authors:** Cao Dianyun, Wang Hongwei, Xu Xiaoxu

**Date:** 2017-11-10T00:00:00+00:00

## Abstract

To elucidate the effects of sulfur fertilizer application rates on crop yield enhancement, this study employed a single-factor randomized block design and conducted a field experiment with five sulfur fertilizer (sulfur) application rates: 0 kg(S) · hm 2 (S0), 40 kg(S) · hm 2 (S1), 80 kg(S) · hm 2 (S2), 120 kg(S) · hm 2 (S3), and 160 kg(S) · hm 2 (S4), to investigate the effects of different sulfur fertilizer application rates on maize yield and nitrogen and sulfur uptake and distribution. The results showed that sulfur fertilizer application increased maize yield by 7.0%~18.1%, with the highest yield observed under the S2 treatment at 12 978.30 kg · hm 2. Sulfur fertilizer application significantly increased plant dry matter accumulation at various growth stages (except the large bell stage). At maturity, dry matter accumulation in maize leaves, leaf sheaths, and grains reached maximum values under the S2 treatment, while dry matter accumulation in stems, husks, and cobs reached maximum values under the S1 treatment. Throughout the entire growth period, sulfur accumulation and sulfur uptake intensity in maize reached maximum values under the S2 treatment, which were significantly higher than those under the S0 treatment without sulfur application. At maturity, sulfur accumulation in maize leaves increased with increasing sulfur application rate, reaching a maximum under the S4 treatment; sulfur accumulation in stems, husks, and cobs was highest under the S1 treatment; and sulfur accumulation in leaf sheaths and grains was highest under the S2 treatment. From the jointing stage to the tasseling and silking stage, the S3 treatment was most effective in promoting nitrogen accumulation in maize; during the filling and maturity stages, the S1 and S2 treatments were more conducive to nitrogen accumulation, respectively. Increasing sulfur application rate decreased the partial factor productivity and use efficiency of sulfur fertilizer in maize to some extent; the agronomic efficiency of sulfur fertilizer was highest under the S2 treatment. The nitrogen and sulfur uptake and accumulation in

maize plants showed an extremely significant correlation. Therefore, appropriate sulfur fertilizer application plays an important role in improving maize yield and the efficiency of nitrogen and sulfur uptake, distribution, and utilization, with the best overall effect achieved at a sulfur application rate of 80 kg(S) · hm 2.

## Full Text

## Effect of Sulfur Fertilizer Application Rate on Nitrogen/Sulfur Uptake, Distribution, and Yield of Maize

**CAO Dianyun, WANG Hongwei**, XU Xiaoxu
Special Maize Institute, Shenyang Agricultural University, Shenyang 110866, China

### Abstract

To clarify the effects of sulfur fertilizer application rates on crop yield improvement, a field experiment was conducted using a single-factor randomized block design with five sulfur (as elemental sulfur) application rates: 0 kg(S) · $hm^{-2}$ (S0), 40 kg(S) · $hm^{-2}$ (S1), 80 kg(S) · $hm^{-2}$ (S2), 120 kg(S) · $hm^{-2}$ (S3), and 160 kg(S) · $hm^{-2}$ (S4). The study investigated the effects of different sulfur application rates on maize yield and nitrogen/sulfur uptake and distribution. The results showed that sulfur application increased maize yield by 7.0%-18.1%, with the highest yield of 12,978.30 kg · $hm^{-2}$ achieved under the S2 treatment. Sulfur application significantly increased plant dry matter accumulation at all growth stages except the large bell stage. At maturity, dry matter accumulation in leaves, leaf sheaths, and grains reached maximum values under the S2 treatment, while accumulation in stems, bracts, and cobs peaked under the S1 treatment. Throughout the growth period, both sulfur accumulation and sulfur uptake intensity in maize reached maximum values under the S2 treatment, which were significantly higher than those under the S0 treatment. At maturity, sulfur accumulation in leaves increased with increasing sulfur application rate, reaching its maximum under the S4 treatment. Sulfur accumulation in stems, bracts, and cobs was highest under the S1 treatment, while accumulation in leaf sheaths and grains was highest under the S2 treatment. From the jointing stage to the silking stage, the S3 treatment was most effective in promoting nitrogen accumulation; at the grain-filling and maturity stages, the S1 and S2 treatments were more conducive to nitrogen accumulation, respectively. Increasing sulfur application rates decreased sulfur partial productivity and sulfur use efficiency to some extent, while sulfur agronomic efficiency reached its maximum under the S2 treatment. There was a highly significant correlation between nitrogen and sulfur accumulation in maize plants. Therefore, appropriate sulfur fertilizer application plays an important role in improving maize yield and the uptake, distribution, and utilization efficiency of nitrogen and sulfur, with an application rate of 80 kg(S) · $hm^{-2}$ producing the best overall results.

**Keywords:** maize; sulfur fertilizer; nitrogen; accumulation amount; absorption intensity; use efficiency; yield

# 1 Materials and Methods

## 1.1 Experimental Site

The experiment was conducted in 2015 in Haicheng City, Liaoning Province (40°53 N, 122°43 E), with an average annual temperature of 10.4 °C and total rainfall of 390.6 mm during the growing season. The soil was a brown earth with the following nutrient concentrations in the 0–20 cm tillage layer: total nitrogen 1.32 $g \cdot kg^{-1}$, available nitrogen 104 $mg \cdot kg^{-1}$, available phosphorus 116.52 $mg \cdot kg^{-1}$, available potassium 98.52 $mg \cdot kg^{-1}$, and available sulfur 16.27 $mg \cdot kg^{-1}$. The local cultivation practice involved continuous maize cropping with a one-time application of slow-release compound fertilizer (675 $kg \cdot hm^{-2}$, N:$P_2O_5$:$K_2O$ = 28:12:12) at sowing, with no additional topdressing.

## 1.2 Experimental Design

A single-factor randomized block design was employed with five sulfur (elemental sulfur) application rates: 0 kg(S) $\cdot hm^{-2}$ (S0), 40 kg(S) $\cdot hm^{-2}$ (S1), 80 kg(S) $\cdot hm^{-2}$ (S2), 120 kg(S) $\cdot hm^{-2}$ (S3), and 160 kg(S) $\cdot hm^{-2}$ (S4). All plots received compound fertilizer at 675 $kg \cdot hm^{-2}$ (N:$P_2O_5$:$K_2O$ = 28:12:12), applied once at sowing. The test maize cultivar was 'Zhengdan 958' , planted at a density of 67,500 plants $\cdot hm^{-2}$ in eight-row plots with 5 m row length, 0.56 m row spacing, and a plot area of 22.4 $m^2$. The experiment had three replications, and field management followed local production practices.

## 1.3 Sampling and Measurements

**1.3.1 Dry Matter Accumulation** At the jointing stage (51 days after emergence), large bell stage (68 days after emergence), silking stage (90 days after emergence), grain-filling stage (109 days after emergence), and maturity stage (135 days after emergence), three representative plants were randomly selected from each treatment. At maturity, plants were separated into stems, leaves, sheaths, bracts, cobs, and grains. All samples were killed at 105 °C for 30 minutes, then oven-dried at 80 °C to constant weight for dry weight measurement. Samples were analyzed to calculate dry matter accumulation, nitrogen accumulation, and sulfur accumulation.

**1.3.2 Plant Nitrogen and Sulfur Content Determination** Plant nitrogen content was determined using the semi-micro Kjeldahl method after $H_2SO_4$-$H_2O_2$ digestion, measured with a FOSS KJELTEC 8100 automatic nitrogen analyzer. Plant sulfur content was determined after $HNO_3$-$HClO_4$-HCl digestion using an ICP-7500A plasma mass spectrometer.

**1.3.3 Yield Measurement** At full maturity, maize from the middle four rows of each plot was harvested, and yield was calculated based on 14% moisture content.

### 1.4 Data Analysis

Sulfur (nitrogen) uptake intensity ($g \cdot hm^{-2} \cdot d^{-1}$) = Net population absorption amount ($g \cdot hm^{-2}$) / Growth duration of each stage (d) [Equation 1]

Sulfur partial productivity = Grain yield in sulfur-treated plots / Sulfur application rate [Equation 2]

Sulfur use efficiency = (Sulfur absorption amount in sulfur-treated plots - Sulfur absorption amount in non-sulfur plots) × 100% / Sulfur application rate [Equation 3]

Sulfur agronomic efficiency = (Grain yield in sulfur-treated plots - Grain yield in non-sulfur plots) / Sulfur application rate [Equation 4]

Experimental data were analyzed using Microsoft Excel 2003 and SPSS 13.0 software for variance analysis and significance testing. Sigmaplot 12.0 was used for graphing.

---

## 2 Results

### 2.1 Effects of Sulfur Application on Maize Dry Matter Accumulation and Distribution

As shown in , sulfur application significantly increased aboveground dry matter accumulation at the jointing stage, though differences among sulfur treatments were not significant. From the large bell stage to maturity, aboveground dry matter accumulation showed a trend of first increasing then decreasing with increasing sulfur application rates. From the silking stage to maturity, the S2 treatment produced the maximum aboveground dry matter accumulation, significantly higher than other treatments. The S4 treatment resulted in the lowest dry matter accumulation at all growth stages, being significantly lower than the S0 treatment at the silking and grain-filling stages.

At maturity, dry matter accumulation in various organs followed the pattern: grain > stem > leaf sheath > leaf > cob > bract. Leaf dry matter accumulation increased with increasing sulfur application rates, reaching its maximum under the S4 treatment. Dry matter accumulation in leaf sheaths, stems, cobs, and grains all showed a trend of first increasing then decreasing with increasing sulfur application rates. Sulfur application had no significant effect on bract dry matter accumulation.

### 2.2 Effects of Sulfur Application on Sulfur Uptake and Distribution in Maize

According to , sulfur accumulation in maize at all growth stages showed a single-peak curve pattern with increasing sulfur application rates, with the S2 treatment producing the maximum sulfur accumulation at each stage. From the jointing to large bell stage, sulfur accumulation among treatments followed the order S2 > S3 > S1 > S0 > S4. At the silking stage, the order was S2 > S1 > S3 > S0 > S4, while from grain-filling to maturity it was S2 > S1 > S3 > S4 > S0.

At maturity, sulfur accumulation in various organs generally followed: grain > leaf > stem > leaf sheath > bract > cob. Leaf sulfur accumulation increased with increasing sulfur application rates, reaching its maximum under the S4 treatment. Sulfur accumulation in leaf sheaths, stems, bracts, and grains all increased initially then decreased with increasing sulfur rates, peaking under the S2 treatment. Cob sulfur accumulation was highest under the S1 treatment.

Sulfur application rate significantly affected sulfur uptake intensity in maize (). Two peaks of sulfur uptake intensity occurred throughout the growth period, at the jointing stage and silking stage. From jointing to silking, sulfur uptake intensity followed the order S2 > S3 > S1 > S0 > S4. At the grain-filling stage it was S2 > S1 > S3 > S4 > S0, and at maturity it was S2 > S1 > S3 > S0 > S4. Overall comparison across treatments showed that a sulfur application rate of 80 $kg \cdot hm^{-2}$ (S2 treatment) was most beneficial for sulfur uptake at all growth stages. The 160 $kg \cdot hm^{-2}$ sulfur application rate resulted in relatively low sulfur accumulation and uptake intensity, indicating that while appropriate sulfur application promotes sulfur uptake intensity, excessive application inhibits sulfur absorption.

### 2.3 Effects of Sulfur Application on Nitrogen Uptake and Distribution in Maize

Appropriate sulfur application significantly increased total nitrogen accumulation in maize, which showed a trend of first increasing then decreasing with increasing sulfur application rates. From jointing to silking, the S3 treatment produced the maximum nitrogen accumulation, being 12.40%, 64.45%, and 37.23% higher than the S0 treatment, respectively. At the grain-filling stage, the S1 treatment showed the highest nitrogen accumulation, 21.43% higher than S0. At maturity, the S2 treatment achieved the maximum nitrogen accumulation, 42.23% higher than S0, with all differences reaching significant levels ($P < 0.05$).

At maturity, nitrogen accumulation in various organs followed the same pattern as sulfur accumulation. Nitrogen accumulation in leaves, leaf sheaths, stems, and grains all reached maximum values under the S2 treatment. Bract nitrogen accumulation peaked under the S3 treatment, while cob nitrogen accumulation was highest under the S1 treatment, all significantly higher than other treatments.

As shown in , from jointing to silking, nitrogen uptake intensity was higher under sulfur application rates of 80 kg · $hm^{-2}$ and 120 kg · $hm^{-2}$ (S2 and S3 treatments), significantly higher than other treatments. From grain-filling to maturity, nitrogen uptake intensity was highest under sulfur application rates of 40 kg · $hm^{-2}$ and 80 kg · $hm^{-2}$ (S1 and S2 treatments), significantly higher than other treatments.

### 2.4 Correlation Analysis Between Sulfur and Nitrogen Accumulation in Maize

There was a highly significant positive correlation between sulfur accumulation and nitrogen accumulation in maize at different growth stages ($P < 0.01$). The correlation coefficient between sulfur and nitrogen accumulation gradually increased with advancing growth stages, reaching its maximum at maturity [Figure 1: see original paper].

### 2.5 Effects of Sulfur on Maize Yield and Sulfur Use Efficiency

As shown in , maize yield showed a trend of first increasing then decreasing with increasing sulfur application rates. The maximum yield of 12,978.3 kg · $hm^{-2}$ was achieved at the S2 sulfur rate, significantly higher than the S0 and S1 treatments but not significantly different from the S3 and S4 treatments. Both sulfur partial productivity and sulfur use efficiency decreased with increasing sulfur application rates, reaching maximum values under the S1 treatment and significantly higher than other treatments. Sulfur agronomic efficiency showed a trend of first increasing then decreasing with increasing sulfur rates, reaching its maximum under the S2 treatment and significantly higher than other sulfur treatments except S1.

---

## 3 Discussion and Conclusion

As the fourth major essential nutrient for plant growth after nitrogen, phosphorus, and potassium, sulfur is an important component for synthesizing amino acids (e.g., cysteine, methionine) in plants. Soil sulfur content is a crucial factor affecting plant growth, development, and yield formation. In recent years, sulfur deficiency in soils has been widely reported. Therefore, appropriate sulfur fertilizer application is an important measure for increasing crop yields. Numerous studies have shown that applying appropriate sulfur fertilizer can increase crop yields by 10%–25%.

Li et al. conducted experiments on the effects of different sulfur application rates on maize yield in soil with available sulfur content of 13.3 mg · $kg^{-1}$, finding that when sulfur application rates were 37.5–112.5 kg · $hm^{-2}$, maize grain yield increased by 8.94%–22.05%, but decreased when sulfur application increased to 150 kg · $hm^{-2}$. In our study, the test soil contained 16.27 mg · $kg^{-1}$ sulfur, indicating potential sulfur deficiency. Sulfur application significantly increased maize yield by 7.0%–18.1%, with maximum yield achieved at 80 kg · $hm^{-2}$, though further increases in sulfur application decreased yield.

The foundation of high maize yield is adequate plant material accumulation, as grain yield is significantly positively correlated with plant dry matter accumulation. Previous studies have shown that combined nitrogen and sulfur application increases crop dry matter accumulation and promotes the translocation of assimilates to grains. Our results are consistent with these findings and further demonstrate that sulfur application rates of 40–120 kg · $hm^{-2}$ maintained high dry matter accumulation throughout the growth period and increased the percentage of grain dry matter in the whole plant.

Many studies have shown that appropriate sulfur application increases maize sulfur accumulation. Our research found that at a sulfur rate of 80 kg · $hm^{-2}$, sulfur accumulation at each growth stage increased by 29.92%–54.64% compared with the non-sulfur treatment. Two peaks of sulfur uptake intensity occurred at the jointing and silking stages, likely because the silking stage represents the transition from vegetative to reproductive growth, increasing sulfur demand.

Sulfur uptake by maize plants directly affects sulfur partial productivity and sulfur agronomic efficiency. Li et al. reported that both sulfur partial productivity and sulfur agronomic efficiency decreased with increasing sulfur application rates. Our results are consistent with these findings and further demonstrate that sulfur agronomic efficiency reached its maximum at 80 kg · $hm^{-2}$, decreasing with further sulfur application. This indicates that excessive sulfur application causes sulfur waste and may be toxic to maize. At the optimal sulfur rate of 80 kg · $hm^{-2}$, both sulfur accumulation and yield reached maximum values, indicating a balanced state between sulfur supply and demand.

Furthermore, at the optimal sulfur rate, sulfur accumulation differed significantly among maize organs, with the highest accumulation in grains, followed by leaves and stems, and the lowest in bracts and cobs. This suggests that sulfur application promotes sulfur translocation from vegetative organs to grains, increasing grain yield and sulfur agronomic efficiency.

In plant metabolism, sulfur and nitrogen are closely linked, with similar physiological functions and assimilation pathways. Wu reported that 60 kg · $hm^{-2}$ sulfur application promoted nitrogen and sulfur accumulation, translocation, and contribution to grains in wheat at flowering. Our study shows that nitrogen accumulation reached its maximum at 80 kg · $hm^{-2}$ sulfur, with further sulfur application inhibiting nitrogen uptake. At the optimal sulfur rate, nitrogen accumulation differed significantly among organs at maturity, with the highest accumulation in grains, followed by leaves, leaf sheaths, and stems, and the lowest in bracts and cobs. This demonstrates that sulfur application promotes nitrogen uptake, which is another important reason for increased grain yield and dry matter accumulation, and indicates that sulfur-nitrogen interaction is crucial for improving maize yield and fertilizer use efficiency.

Zhou et al. reported that nitrogen and sulfur promote each other at appropriate supply levels but inhibit each other at excessive levels, which is detrimental to crop growth. Wang et al. found that nitrogen accumulation was highly significantly positively correlated with sulfur accumulation in wheat. Our study also confirmed a highly significant positive correlation between nitrogen and sulfur accumulation in maize, with correlation coefficients increasing as growth stages progressed.

In conclusion, our experiments with different sulfur application rates demonstrate that sulfur application at 80–120 $kg \cdot hm^{-2}$ promotes sulfur and nitrogen uptake and increases maize yield, providing an important reference for local maize production.

---

## References

[1] Liu Y, Shi H Q, Gong Y H. Effects of sulfur and nitrogen fertilizer combination on nitrogen transfer and senescence in stay-green wheat[J]. Acta Botanica Boreali-Occidentalia Sinica, 2012, 32(6): 1206–1213
[2] Wang L, Gao X Z, Ma W Q, et al. Sulphur consumption in Chinese agriculture: Situation and outlook[J]. Plant Nutrition and Fertilizer Science, 2008, 14(6): 1219–1226
[3] Caviglia O P, Melchiori R J M, Sadras V O. Nitrogen utilization efficiency in maize as affected by hybrid and N rate in late-sown crops[J]. Field Crops Research, 2014, 168: 27–37
[4] Xie R Z, Dong S T, Hu C H, et al. The difference of sulfate uptake and utilization in maize (Zea mays L.) . The difference genotypes in absorption and utilization of sulfate[J]. Acta Agronomica Sinica, 2004, 30(1): 52–59
[5] Wang K J, Hu C H, Dong S T. The sulfur absorption and spatio-temporal distributing in high-yield summer maize[J]. Acta Agronomica Sinica, 2000, 26(6): 899–904
[6] Zhou J, Wang D, Man J G, et al. Effects of interaction of nitrogen and sulfur on seedling growth, uptake and utilization of nitrogen and sulfur of winter wheat under high nitrogen conditions[J]. Plant Nutrition and Fertilizer Science, 2012, 18(1): 42–51
[7] Li H M, Wang B L. Research progress on maize sulfur nutrition status and its utilization[J]. Journal of Agricultural Science and Technology, 2008, 10(4): 16–21
[8] Zhao Y X, Zhou F, Li X F, et al. Effects of nitrogen and sulfur interaction on their accumulation, translocation and use efficiency in winter wheat[J]. Chinese Journal of Eco-Agriculture, 2014, 22(9): 1020–1028
[9] Liu S Z, He H J, Feng G, et al. Effects of nitrogen and sulfur supply on the growth and organo-sulfur compounds of Zhangqiu spring onion[J]. Plant Nutrition and Fertilizer Science, 2009, 15(4): 884–889
[10] Liu S Z, Chen Q, Feng G, et al. Effects of nitrogen and sulfur supply on sulfur-containing compounds and activities of key enzymes for sulfur metabolism

in Chinese spring onion[J]. Acta Agriculturae Boreali-Occidentalis Sinica, 2010, 19(6): 100-105
[11] Liu Q. Effects of nitrogen forms and sulphur rate on nitrogen, sulphur and potassium nutrition of tobacco[J]. Chinese Journal of Soil Science, 2006, 37(6): 1171-1174
[12] Zhang C A, Zhang M, Zeng Y C. Effects of sulfur on chemical properties of calcareous soil[J]. Chinese Journal of Applied Ecology, 2007, 18(7): 1453-1458
[13] Rahman M M, Soaud A A, Al Darwish F H, et al. Effects of sulfate uptake and utilization in maize using acidified water[J]. African Journal of Biotechnology, 2011, 10(42): 8345-8351
[14] Rahman M M, Soaud A A, Al Darwish F H, et al. Growth and nutrient uptake of maize plants as affected by elemental sulfur and nitrogen fertilizer in sandy calcareous soil[J]. African Journal of Biotechnology, 2011, 10(60): 12882-12889
[15] Wang D, Yu Z W, Wang X D. Effect of sulfur fertilizer on sulfur absorption and distribution and yield of winter wheat[J]. Acta Agronomica Sinica, 2003, 29(5): 791-793
[16] Ahmad A, Abraham G, Abdin M Z. Biochemical evaluation of sulfur and nitrogen assimilation potential of mustard (Brassica juncea L. Czern. & Coss.) under application of slow-release sulfur fertilizer[J]. Applied Biochemistry and Biotechnology, 2001, 96(1): 167-172
[17] Lakkineni K C, Abrol Y P. Sulphur requirement of crop plants, physiological analysis[J]. Fertiliser News, 1994, 39(3): 11-18
[18] Fitzgerald M A, Ugalde T D, Anderson J W. Sulphur nutrition affects delivery and metabolism of S in developing endosperms of wheat[J]. Journal of Experimental Botany, 2001, 52(360): 1519-1526
[19] Wang G P, Xiang P H, Zeng H Y, et al. Effect of different sulphur application rates on leaf yield and quality of flue-cured tobacco[J]. Crop Research, 2009, 23(1): 35-37
[20] Li N, Yang Y, Zhao Y X, et al. Effects of sulfur application rate on sulfur utilization and grain yield of summer maize in Guanzhong Plain[J]. Agricultural Research in the Arid Areas, 2013, 31(5): 168-172
[21] Zhu C H, Zhang J L, Wang X L, et al. Effects of combined application of silicon and phosphorus fertilizers on dry matter accumulation and distribution and grain yield of spring maize in low phosphorus soils[J]. Chinese Journal of Eco-Agriculture, 2016, 24(6): 725-735
[22] Wang L, Wang D, Zhou J, et al. Interactive effects of nitrogen and sulfur on flag leaf senescence, yield and nitrogen use efficiency of winter wheat[J]. Acta Pedologica Sinica, 2016, 53(6): 1476-1488
[23] Xie Y X, Liu C, Zhu Y J, et al. Effects of nitrogen and sulfur combined application on nitrogen use efficiency and grain yield of winter wheat[J]. Plant Nutrition and Fertilizer Science, 2015, 21(1): 64-71
[24] Wang X Y, Jiang W, Zhang H S. Effects of sulphur supply at different stages on the sulphur accumulation and grain quality of summer maize[J]. Chinese Agricultural Science Bulletin, 2011, 27(30): 131-134
[25] Koprivova A, Suter M, den Camp R O, et al. Regulation of sulfate assimi-

lation by nitrogen in Arabidopsis[J]. Plant Physiology, 2000, 122(3): 737-746
[26] Tabe L M, Droux M. Limits to sulfur accumulation in transgenic lupin seeds expressing a foreign sulfur-rich protein[J]. Plant Physiology, 2002, 128(3): 1137-1148
[27] Wu L. Study on regulation of sulfur and nitrogen fertilizer combined application on material accumulation remobilization yield in winter wheat[D]. Zhengzhou: Henan Agricultural University, 2010: 38-40
[28] Wang D, Sang X G, Zhou J, et al. Differences accumulation and distribution and use efficiency of nitrogen and sulfur in different types of winter wheat[J]. Scientia Agricultura Sinica, 2010, 43(22): 4587-4597

*Note: Figure translations are in progress. See original paper for figures.*