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RESEARCH ARTICLE

Impact of nitrogen and sulphur fertilizer rates on nitrogen uptake dynamics and nutrient use efficiency in wheat

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Abstract

A field experiment was performed to assess the impact of nitrogen (N) and sulphur (S) fertilizer rates, along with their interactions, on nutrient uptake, content and nitrogen use efficiency (NUE) in wheat at various growth stages. The study examined the effects of administering 40 kg N, 80 kg N, and 120 kg N alongside 0 kg S, 15 kg S, and 30 kg S on N and S uptake, as well as grain and shoot nutrient content during wheat ontogeny. Nitrogen uptake and concentration in wheat grain and shoots were significantly increased by 120 kg of N and 30 kg of S. At 120 kg N + 30 kg S, shoots (13.91, 34.80, 41.50 and 39.89 kg ha^{-1}) and grains (152.36 kg ha^{-1}) showed the highest uptake, with the lowest recorded in the control. Sulphur uptake followed a similar pattern, peaking at 120 kg N + 30 kg S (3.17, 6.91 and 8.36 kg ha^{-1}) in the shoots. This treatment had the highest S levels in shoots (0.67%, 0.44%, and 0.34%) and grain (0.288%) compared to the control group. The 120 kg N + 30 kg S treatment had the highest NUE and sulphur use efficiency (SUE) (91.31% and 84.10%, respectively), while the 40 kg N + 0 kg S and 40 kg N + 15 kg S treatments recorded the lowest values (53.14% and 11.03%). Nitrogen production efficiency peaked at 21.187 kg yield kg^{-1} N at 120 kg N and 0 kg S, but S production efficiency decreased with higher S levels. Balancing N and S improved nutrient absorption, content, and utilization efficiency in the wheat production system.

Keywords

ammonium nitrate; kieserite; NUE; sustainability; wheat ontogeny

Introduction

Wheat (*Triticum aestivum*) is a staple crop and a critical component of global food security, supplying essential nutrients to millions of people worldwide. Wheat requires an adequate supply of essential nutrients, such as nitrogen (N) and sulphur (S), to achieve optimal growth and yield. Global production systems vary significantly in both climatic conditions and soil fertility (1). All agricultural systems must supply plants with sufficient nutrients in appropriate quantities. Typically, fertilizers are used to deliver nutrients in regions with advanced production systems. Mineral fertilizers are essential for addressing nutritional deficiencies in plants, improving agricultural productivity, and mitigating losses in yield quantity and quality (2). In 2022, the demand for nitrogen fertilizers reached 62.0 million tons in Asia, 25.0 million tons in the Americas, and 17.6 million tons in Europe. Simultaneously, there is increasing emphasis on reducing fertilizer application due to environmental considerations. Inadequate management of N fertilization can diminish wheat output and result in nutrient losses through leaching, runoff, volatilization, or denitrification. Consequently, optimizing the application of N fertilizers is crucial for ensuring the economic sustainability of cropping systems and facilitating appropriate plant production, while simultaneously mitigating environmental risks associated with excess N (3). This research domain has emerged as a primary emphasis in modern agricultural studies, primarily because N fertilizer constitutes the most significant input expense, and its price keeps rising due to demand and production expenses. Appropriate plant nutrition, among other nutrients, is essential for efficient nitrogen fertilization. The impact of N and S fertilizers on crop yield has been extensively studied, and these elements are typically regarded as essential components in cereal cultivation. This is due to their influence on accelerated plant development and enhancement of both the quality and quantity of grain yield. Grain protein content is a key factor influencing wheat grain quality and it is significantly affected by N and S fertilization. These macronutrients serve as the fundamental components of proteins. N fertilization enhances grain protein content, while sulphur fertilization influences grain protein composition. Sulphur is an essential component of sulphur-containing amino acids like cysteine and methionine, which are the building blocks for proteins. Sulphur works synergistically with N in protein synthesis. A balanced S:N ratio ensures efficient nitrogen metabolism, leading to enhanced protein accumulation. Without sufficient S, N assimilation is impaired, reducing the synthesis of proteins in wheat grains. Insufficient S availability prevents wheat from achieving its maximum yield potential (4). The utilization of nitrogen for protein synthesis may be diminished.

As the human population expands and food consumption rises, crop productivity must be enhanced by approximately 70% by 2050 and increased fourfold or tripled by 2100 to provide food security (5). Investigating methods to enhance plant output and optimize the utilization of nitrogen fertilizers without compromising environmental integrity is a significant research domain. Understanding nutrient assimilation and utilization efficiency is vital for sustainable wheat productivity. Nitrogen and S fertilizers play pivotal roles in these processes (5). Ammonium nitrate, a widely used nitrogen fertilizer that supplies both ammonium (NH_4^+) and nitrate (NO_3^-) ions, is frequently used to supply nitrogen to crops. This dual-nitrogen form guarantees that plants have access to readily available nitrogen at all stages of their development. Ammonium nitrate encourages vigorous vegetative growth and increases grain yield; however, its efficacy can be affected by a variety of factors, such as the timing and rate of application. Similarly, S typically supplied as kieserite (magnesium sulfate), not only rectifies S deficiencies but also supports enzymatic activation and chlorophyll production (6).

The overall quality of wheat cereals is improved by the combination of S and N, which enhances protein synthesis. The efficiency of nutrient uptake and utilization can be substantially influenced by the interaction between N from ammonium nitrate and S from kieserite. The efficient use of nutrients can be optimized through the proper management of these fertilizers, resulting in enhanced crop growth, a reduced environmental impact and an increase in yield. Nevertheless, the dynamics of nitrogen assimilation during wheat growth and the efficacy of various N and S rates have not been thoroughly investigated, particularly with respect to their combined effects (7).

The objective of this study is to examine the impact of the time course of nitrogen assimilation during wheat ontogeny and its response to varying N and S fertilizer rates. The study will also evaluate how the rates affect nutrient use efficiency and its constituents. The findings are expected to provide actionable recommendations for fertilizer management, emphasizing sustainable practices that optimize nutrient utilization, reduce environmental impacts and increase crop productivity. These outcomes align with the broader goals of sustainable agriculture and global food security.

Material and Methods

Experimental design and setup

A field experiment was conducted at the research farm of Lovely Professional University, Phagwara. The agricultural field is in the northern plain zone, with coordinates at latitude 31ºN and longitude 75.25ºE. The site experiences sub-tropical type of climate. The experiment was set up using a randomized block design. There was a total of 10 treatments and the plot was 5 m × 4 m in size, with a row-to-row distance of 22.5 cm. The wheat crop was sown on November 14, using the HD3086 variety, which matures in approximately 148 days. Each treatment was replicated three times. The treatments are listed in Table 1.

Table 1. Detail of the treatments

Treatments	Description
T_0	Control
T_1	40 kg N + 0 kg S
T_2	80 kg N + 0 kg S
T_3	120 kg N + 0 kg S
T_4	40 kg N + 15 kg S
T_5	80 kg N + 15 kg S
T_6	120 kg N + 15 kg S
T_7	40 kg N + 30 kg S
T_8	80 kg N + 30 kg S
T_9	120 kg N + 30 kg S

Ammonium nitrate was the nitrogen source employed in this investigation. Forty kilograms of N applied from ammonium nitrate before sowing. Eighty kilograms of N: 40 Kg N at sowing and 40 Kg N at the beginning of shooting. One hundred twenty kilograms N: 40 Kg N at sowing, 40 Kg N at the beginning of shooting and 40 Kg N at heading. Kieserite was used to apply 10 kg and 20 kg of S before sowing. Furthermore, 5 kg and 10 kg of S were applied as a foliar spray in the form of $MgSO_4.7H_2O$. Single superphosphate (SSP) was administered at a rate of 387 kg ha^{-1} before the cultivation of wheat. Foliar application of $MgSO_4$ is a quick way to correct Mg deficiencies during critical growth stages. Kieserite is a natural mineral used as a soil amendment to supply Mg and S in a readily available form. During the initial phase of vegetation, a 50% dosage of nitrogen was administered. Additionally, a 30% dosage was administered prior to the commencement of the stem elongation phase. In addition, a 20% N dosage was administered prior to heading. The wheat crop was harvested when the spikelets reached full maturity, and the quantity of grain yield was subsequently evaluated. Five to six irrigations were provided to the crop at crown root initiation, tillering, jointing, booting flowering and milky stage/soft dough. Fifty to seventy-five millimeter of water was provided during each irrigation by surface irrigation method. After the plants attained physiological maturity, the harvesting process was implemented. Data was collected in accordance with the methodology delineated below.

Nutrient (N, P and K) uptake by plants (kg ha^{-1})

The nitrogen, phosphorus and potassium concentrations of wheat grain and straw were determined using the Micro Kjeldahl method, the Vanado-Molybdate Phosphoric Yellow Color method and the Flame Photometric method, respectively (8, 9). Nutrient uptake was computed by using the subsequent formula.:

$$Nutrient\ (NPK)\ uptake = \frac{Nutrient\ (NPK)\% \times Yield\ (grain\ or\ straw)}{100}$$

Nitrogen content in grain and plant

To determine nitrogen content, 0.2 g of ground plant or grain samples was digested with concentrated $HClO_4$ and a $CuSO_4 \cdot K_2SO_4$ mixture at 450°C for 4-5 hours. The digested solution was diluted to 100 mL using distilled water. A 20 mL aliquot was distilled with NaOH and the released ammonia was absorbed in a boric acid indicator. The distillate was titrated with 0.005 N HCl until the solution turned light pink. Nitrogen content was calculated from the titration reading (10, 11).

Sulphur content in plants

A 0.5 g oven-dried, ground leaf sample was digested overnight in concentrated HNO_3 and subsequently heated with perchloric acid until the solution became clear. The digested mixture was diluted to 100 mL using distilled water and then filtered. A 5 mL aliquot of the extract was mixed with reagents, including a mixed acid reagent, acid sulphate, sorbitol solution and barium chloride for analysis. After thorough mixing, the absorbance was measured at 420 nm, and sulphur content was calculated using a standard curve (12).

Nutrient use efficiency

The nutrient (N, P, K, and S) uptake by grain and straw was estimated by following formulae (9).

$$Nutrient\ use\ efficieny\ (\%) = \frac{Uptake\ from\ treated\ plot - Uptake\ from\ control\ plot}{\text{Total fertilizer applied}} \times 100$$

Statistical Analysis

Conventional statistical methodology was employed for data analysis. The SPSS (Statistical Package of Social Services Version 2022) program was used for the analyses of variance (ANOVA), quadratic equation and regression curves. The mean was analyzed for the interaction effect of N and S using the least significant difference (LSD) test at $p \leq 0.05$.

Results

Effect of N and S fertilizer rates and their interactions on N uptake and content in wheat at different growth stages

Nutrient uptake in shoot at tillering, pre-anthesis and dough stage of wheat under different fertilizer levels is presented in Table 2. The treatments significantly affected grain and shoot nitrogen contents and nitrogen uptake. A significant enhancement in grain N uptake was observed with the application of 40 kg, 80 kg, and 120 kg N compared to the control across all S levels (0 kg, 15 kg, and 30 kg S). It was shown that 120 kg N exhibited a considerably higher enhancement in grain and shoot N uptake under 0 kg, 15 kg, and 30 kg S as compared to 40 kg and 80 N. Moreover, 40 kg and 80 kg N exhibited statistical

Table 2. Effect of different levels of fertilizers and utilization of nitrogen and sulphur on nitrogen uptake in shoot tillering, pre-anthesis and dough stage, uptake (kg ha^{-1}) in grain and shoot at maturity stage of wheat crop

Treatments	N uptake kg ha^{-1} in shoot at tillering stage	N uptake kg ha^{-1} in shoot at pre anthesis stage	N uptake kg ha^{-1} in shoot at dough stage	N uptake kg ha^{-1} in grain at maturity stage	N uptake kg ha^{-1} in shoot at maturity stage
T_0 - Control	1.44±0.11^{f}	13.18±1.49^{g}	9.26±0.96^{g}	43.69±1.78^{h}	8.60±0.45^{g}
T_1 - 40 kg N + 0 kg S	3.05±0.73^{e}	15.14±0.94^{fg}	21.39±1.70^{f}	91.68±1.73^{g}	15.66±0.43^{f}
T_2 - 80 kg N + 0 kg S	3.67±0.41^{e}	21.06±1.25^{e}	26.28±0.53^{de}	103.90±1.20^{f}	22.91±0.79^{d}
T_3 - 120 kg N + 0 kg S	5.20±0.35^{d}	24.96±1.58^{cd}	28.99±1.62^{bcd}	132.25±1.87^{c}	31.71±1.43^{b}
T_4 - 40 kg N + 15 kg S	2.67±0.10^{ef}	16.48±1.98^{f}	25.70±1.14^{de}	114.84±1.99^{e}	18.20±0.21^{ef}
T_5 - 80 kg N + 15 kg S	3.80±0.56^{e}	22.82±0.88^{de}	28.51±1.42^{cde}	114.53±1.51^{e}	23.22±0.18^{d}
T_6 - 120 kg N + 15 kg S	9.28±0.87^{b}	31.16±0.89^{b}	31.69±2.30^{bc}	147.70±2.65^{b}	32.54±2.01^{b}
T_7 - 40 kg N + 30 kg S	3.09±0.21^{e}	16.73±1.09^{f}	25.19±0.55^{e}	115.26±1.94^{e}	20.85±1.89^{de}
T_8 - 80 kg N + 30 kg S	6.90±0.87^{c}	27.65±1.07^{c}	32.45±2.26^{b}	123.14±1.37^{d}	28.03±2.74^{c}
T_9 - 120 kg N + 30 kg S	13.91±1.16^{a}	34.80±2.33^{a}	41.50±2.48^{a}	152.36±0.28^{a}	39.89±1.31^{a}

equivalence in grain nitrogen levels at 0 kg, 15 kg, and 30 kg S.

Nutrient uptake in wheat shoots at tillering, pre anthesis, dough stage and at maturity was recorded as highest (13.91, 34.80, 41.50 and 39.89 kg ha^{-1}) with the application of 120 kg N + 30 Kg S which is found to be significant when compared to other treatments at tillering, pre-anthesis and dough stage. While the lowest (1.44, 13.18, 9.26, and 8.6 kg ha^{-1}) uptake of nutrients in the wheat shoot was recorded in control at tillering, pre-anthesis and dough stage. N uptake at maturity by grain has been recorded as maximum (152.36 kg ha^{-1}) with the application of 120 kg N + 30 kg S and recorded as minimum (43.69 kg ha^{-1}) in control.

Nitrogen content in the shoot and grain at 40 kg, 80 kg, and 120 kg N showed considerable improvement as compared to 0 kg N under 0 kg, 15 kg, and 30 kg S. The results indicated that 120 kg N exhibited a significant difference in N content augmentation compared to 40 kg and 80 kg under 0 kg, 15 kg, and 30 kg S conditions. Furthermore, 40 kg and 80 kg N exhibited statistical similarity. Nonetheless, 80 kg N had markedly superior performance relative to 40 kg N under 30 kg S concerning improvement in N content. The application of treatments 40 kg, 80 kg, and 120 kg N varied much for improvement beyond 0 kg N under 0 kg, 15 kg, and 30 kg S. Nitrogen content in shoot at tillering, pre-anthesis and dough stage of wheat under different levels of fertilizers and utilization of nitrogen and Sulphur data was presented in Table 3.

Nitrogen content in wheat shoots was recorded highest (2.96%, 2.24%, and 1.71%**)** at tillering, pre-anthesis, and dough stages with the application of 120 kg N + 30 kg S**.** While lowest 1.87, 1.56 and 1.15% nitrogen content in wheat shoot was recorded in control at tillering, pre-anthesis and dough stage. Grain N content was highest (2.36%**)** with 120 kg N + 30 kg S and lowest (1.21%**)** in the control.

Effect of N and S fertilizer rates and their interactions on S uptake and content in wheat at different growth stages

Compared to 0 kg N, the addition of 40 kg, 80 kg, and 120 kg N significantly increased S concentration and uptake. Treatment 120 kg N remained significantly different than 40 kg and 80 kg N for improvement in the S concentration and uptake in plants under 0 kg, 15 kg, and 30 kg S. It was also recorded that 80 kg N was significantly better than 40 kg N for the S concentration under the 15 kg and 30 kg S but remained non-significant under 0 kg S.

Sulphur uptake in shoot at tillering, pre-anthesis and dough stages of wheat under different levels of fertilizers and utilization of N and S data were presented in Table 4. Nutrient uptake in wheat shoot was recorded as highest (3.17, 6.91 and 8.36 kg ha^{-1}) under 120 Kg N + 30 Kg S which is found to be significant when compared to other treatments at tillering, pre-anthesis and dough stage. While lowest (0.24, 1.05 and 0.92 S kg ha^{-1}) uptake of nutrient in wheat shoot was recorded in control at tillering, pre-anthesis and dough stage. Nutrient uptake in wheat grain and shoot was recorded as highest (17.99 and 9.70 kg ha^{-1}) in 120 Kg N + 30 Kg S which is found to be significant when compared to other treatments at the maturity. While the lowest 4.15 and 3.01 kg ha^{-1} uptake of nutrients in the wheat grain and shoot was recorded in control at the maturity stage.

Sulphur content in shoot at tillering, pre-anthesis and dough stage of wheat under different levels of fertilizers and utilization of N and S were analyzed and data were presented in Table 5. Sulphur content in wheat shoot was recorded highest (0.67%, 0.44%, and 0.34%) in 120 Kg N + 30 Kg S which is found to be significant when compared to other treatments at tillering, pre-anthesis and dough stage. While the lowest (0.31%, 0.13%, and 0.11%) content of S in wheat shoot was recorded in control at tillering, pre-anthesis and dough stage. Sulphur content in wheat grain and shoot was recorded highest 0.288 and 0.155% in 120 Kg N + 30 Kg S which is found to be significant when compared to other treatments at maturity. While the lowest 0.115 and 0.083% content of S in wheat grain and shoot was recorded in control at maturity stage. Sulphur is a essential component of amino acids like methionine, cysteine, and cystine, which are essential for protein synthesis. Higher S availability enhances protein content in wheat grain, improving its

Table 3. Effect of different levels of fertilizers and utilization of nitrogen and sulphur on nitrogen content (%) in shoot tillering, pre-anthesis and dough stage, grain and shoot at maturity stage of wheat crop

Treatments	N content % in shoot at tillering stage	N content % in shoot at pre an-thesis stage	N content % in shoot at dough stage	N content % in grain at maturity stage	N content % in shoot at maturity stage
T_0 - Control	1.87±0.09^{f}	1.56±0.04^{c}	1.15±0.02^{h}	1.21±0.02^{f}	0.24±0.00^{f}
T_1 - 40 kg N + 0 kg S	2.45±0.03^{e}	1.61±0.02^{c}	1.39±0.03^{g}	2.04±0.02^{e}	0.35±0.01^{e}
T_2 - 80 kg N + 0 kg S	2.67±0.03^{cd}	1.94±0.03^{b}	1.52±0.02^{ef}	2.15±0.01^{d}	0.47±0.02^{c}
T_3 - 120 kg N + 0 kg S	2.81±0.02^{b}	2.15±0.02^{a}	1.62±0.04^{bc}	2.34±0.02^{b}	0.56±0.02^{b}
T_4 - 40 kg N + 15 kg S	2.49±0.05^{e}	1.60±0.16^{c}	1.48±0.03^{f}	2.27±0.02^{c}	0.36±0.00^{e}
T_5 - 80 kg N + 15 kg S	2.73±0.05^{bc}	1.93±0.03^{b}	1.55±0.02^{de}	2.34±0.03^{b}	0.48±0.00^{c}
T_6 - 120 kg N + 15 kg S	2.91±0.02^{a}	2.18±0.02^{a}	1.65±0.02^{b}	2.44±0.02^{a}	0.54±0.03^{b}
T_7 - 40 kg N + 30 kg S	2.61±0.03^{d}	1.69±0.02^{c}	1.48±0.02^{f}	2.29±0.01^{c}	0.41±0.03^{d}
T_8 - 80 kg N + 30 kg S	2.72±0.06b^{c}	2.10±0.09^{a}	1.58±0.02^{cd}	2.36±0.02^{b}	0.54±0.04^{b}
T_9 - 120 kg N + 30 kg S	2.96±0.02^{a}	2.24±0.03^{a}	1.71±0.02^{a}	2.44±0.03^{a}	0.64±0.03^{a}

Table 4. Effect of different levels of fertilizers and utilization of nitrogen and sulphur on sulphur uptake (kg ha^{-1}) in shoot at tillering, pre-anthesis and dough stage, sulphur uptake (kg ha^{-1}) in grain and in shoot of wheat crop

Treatments	S uptake kg ha^{-1} in shoot at tillering stage	S uptake kg ha^{-1} in shoot at pre anthesis stage	S uptake kg ha^{-1} in shoot at dough stage	S uptake kg ha^{-1} in grain at maturity stage	S uptake kg ha^{-1} in shoot at maturity stage
T_0 - Control	0.24±0.02^{f}	1.05±0.07^{g}	0.92±0.13^{g}	4.15±0.21^{e}	3.01±0.16^{f}
T_1 - 40 kg N + 0 kg S	0.55±0.17^{def}	1.20±0.06^{fg}	1.69±0.17^{f}	6.15±0.05^{d}	4.04±0.24^{e}
T_2 - 80 kg N + 0 kg S	0.63±0.05^{de}	1.57±0.09^{f}	2.36±0.04^{e}	10.00±1.24^{c}	5.15±0.26^{d}
T_3 - 120 kg N + 0 kg S	0.89±0.06^{d}	2.61±0.15^{e}	3.97±0.27^{d}	12.23±0.36^{b}	6.62±0.19^{bc}
T_4 - 40 kg N + 15 kg S	0.53±0.02^{ef}	2.39±0.10^{e}	3.40±0.23^{d}	7.42±0.27^{d}	5.28±0.09^{cd}
T_5 - 80 kg N + 15 kg S	0.81±0.13^{de}	4.62±0.32^{d}	5.20±0.20^{c}	12.38±1.21^{b}	6.04±0.12^{cd}
T_6 - 120 kg N + 15 kg S	2.08±0.19^{b}	6.22±0.16^{b}	6.23±0.39^{b}	16.77±0.08^{a}	9.08±0.92^{a}
T_7 - 40 kg N + 30 kg S	0.65±0.04^{de}	2.43±0.20^{e}	3.58±0.22^{d}	7.46±0.23^{d}	5.97±0.19^{cd}
T_8 - 80 kg N + 30 kg S	1.64±0.25^{c}	5.19±0.06^{c}	6.21±0.46^{b}	13.41±0.35^{b}	7.20±0.24^{b}
T_9 - 120 kg N + 30 kg S	3.17±0.27^{a}	6.91±0.44^{a}	8.36±0.50^{a}	17.99±0.45^{a}	9.70±0.79^{a}

Table 5. Effect of different levels of fertilizers and utilization of nitrogen and sulphur on sulphur content (%) in shoot at tillering, pre-anthesis and dough stage, sulphur content (%) in grain and shoot, protein content (%) in grains at maturity stage of wheat crop

Treatments	S content % in shoot at tillering stage	S content % in shoot at pre anthesis stage	S content % in shoot at dough stage	S content % in grain at maturity stage	S content % in shoot at maturity stage
T_0 - Control	0.31±0.03^{f}	0.13±0.004^{f}	0.11±0.004^{i}	0.115±0.004^{e}	0.083±0.002^{f}
T_1 - 40 kg N + 0 kg S	0.44±0.03^{e}	0.13±0.003^{f}	0.11±0.005^{i}	0.137±0.002^{de}	0.090±0.005^{ef}
T_2 - 80 kg N + 0 kg S	0.46±0.02^{de}	0.15±0.004^{e}	0.14±0.002^{h}	0.207±0.025^{c}	0.106±0.005^{de}
T_3 - 120 kg N + 0 kg S	0.48±0.01^{cd}	0.23±0.004^{d}	0.22±0.005^{e}	0.216±0.003^{c}	0.117±0.004^{cd}
T_4 - 40 kg N + 15 kg S	0.49±0.00	0.23±0.003^{cd}	0.20±0.004^{g}	0.146±0.003^{d}	0.104±0.003^{de}
T_5 - 80 kg N + 15 kg S	0.58±0.00^{b}	0.39±0.016^{b}	0.28±0.004^{d}	0.253±0.025^{b}	0.124±0.002^{c}
T_6 - 120 kg N + 15 kg S	0.65±0.00^{a}	0.43±0.002^{a}	0.32±0.003^{b}	0.277±0.002^{ab}	0.150±0.016^{ab}
T_7 - 40 kg N + 30 kg S	0.55±0.00^{b}	0.25±0.003^{c}	0.21±0.006^{f}	0.148±0.004^{d}	0.118±0.002^{cd}
T_8 - 80 kg N + 30 kg S	0.64±0.02^{a}	0.40±0.002^{b}	0.30±0.007^{c}	0.257±0.003^{b}	0.138±0.002^{b}
T_9 - 120 kg N + 30 kg S	0.67±0.00^{a}	0.44±0.003^{a}	0.34±0.004^{a}	0.288±0.003^{a}	0.155±0.010^{a}

quality.

Impact of N and S fertilizer rates and their interactions on nutrient use efficiency, production efficiency and response efficiency in wheat ontogeny

Highest production efficiency (21.187 kg Kg^{-1} N) was recorded in plots treated with 120 kg N + 0 kg S, which was at par with 120 Kg N + 30 Kg S (21.05 kg Kg^{-1}N). The application of 40 Kg N + 30 Kg S ha^{-1} produced the second highest N production efficiency, whereas the lowest production efficiency (18.38%) was observed in plots treated with 40 Kg N + 0 Kg S.

The productive efficiency of S, displayed a decreasing trend with increasing levels of S (Table 6). The highest efficiency (444.8 g) recorded in 0 kg Sand lowest in 15 kg S (151.255 g). Productive efficiency of S decreased with increasing N levels, the highest efficiency recorded at 40 kg Nand lowest in 120 kg N. The highest response of N (36.11 kg) yield increased by applying 40 kg N + 30 kg S with 26.98 kg yield. The response of S mean data indicated that the response of S recorded highest at lower level of S 15 kg and decreased as levels progressed. The highest response of S (82 kg yield increased) was recorded in 120 kg N + 15 kg S whereas the lowest response of S (48.14 kg) was recorded in 40 kg N + 30 kg S. The highest NUE (91.31%) was recorded in 120 Kg N + 30 Kg S which was at par with 80 Kg N + 30 Kg S with 90.56% and followed by 120 Kg N + 15 Kg S. The lowest NUE (53.14) was recorded in 40 Kg N + 0 Kg S. Similarly, the highest SUE (84.10 %) was recorded in 120 Kg N + 30 Kg S which was followed by 80 Kg N + 30 Kg S. The lowest SUE (11.03%) was observed in plots treated with 40 Kg N + 15 Kg S.

Discussion

The study's results highlight the substantial impact of N and S fertilization on nutrient absorption in wheat (*T. aestivum* L.) shoots across different growth stages including tillering, pre-anthesis, dough stage, and maturity. The results indicate that higher N levels (120 kg) combined with S (30 kg) significantly ($p<0.05$) improved nutritional absorption relative to lower N dosages (40 kg and 80 kg) and the control group (0 kg). This trend of

Table 6. Effect of nitrogen and sulphur on production efficiency, yield increase, and nutrient use efficiency in wheat

Treatments	Production efficiency of N (kg grain production kg^{-1} N taken Up)	Production efficiency of S (g grain production kg^{-1} S taken Up)	Response of N (Increase in yield kg^{-1} of nutrient applied)	Response of S (Increase in yieldkg^{-1} of nutrient applied)	Nitrogen use efficiency %	Sulphur use efficiency %
T_0 - Control	_	_	_	_	_	_
T_1 - 40 kg N + 0 kg S	18.381±0.581^{cd}	444.88±16.25^{a}	22.07±1.83^{c}	_	53.74±0.630618^{g}	_
T_2 - 80 kg N + 0 kg S	18.396±0.545^{cd}	196.037±38.687^{c}	13.86±1.05^{f}	_	71.93±1.90914^{d}	_
T_3 - 120 kg N + 0 kg S	21.187±0.488^{a}	232.324±5.207^{c}	15.63±0.04^{ef}	_	73.86±1.914133^{d}	_
T_4 - 40 kg N + 15 kg S	15.172±0.187^{e}	330.807±7.669^{b}	26.98±0.34^{b}	71.96±0.91^{b}	58.22±0.395406^{f}	11.03±1.13^{f}
T_5 - 80 kg N + 15 kg S	17.132±1.200^{d}	151.225±30.699^{d}	15.18±1.11^{ef}	80.93±5.95^{a}	86.67±1.3293^{c}	30.87±0.96^{d}
T_6 - 120 kg N + 15 kg S	19.046±0.287^{bc}	156.967±0.927^{d}	16.50±0.33^{e}	82.00±2.60^{a}	88.56±0.341185^{bc}	46.11±2.12^{c}
T_7 - 40 kg N + 30 kg S	20.190±0.466^{ab}	441.576±48.576^{a}	36.11±0.30^{a}	48.14±0.39^{c}	67.60±0.366387^{e}	21.76±0.47^{e}
T_8 - 80 kg N + 30 kg S	18.927±0.985^{bc}	162.304±5.865^{d}	18.80±1.08^{d}	50.12±2.88^{c}	90.56±1.378608^{ab}	54.86±6.76^{b}
T_9 - 120 kg N + 30 kg S	21.053±0.721^{a}	165.457±1.578^{d}	19.08±0.93^{d}	76.30±3.70^{ab}	91.31±1.118881^{a}	84.10±1.87^{a}

enhanced nutrient absorption with increased N and S combinations corresponds with the critical function of these nutrients in facilitating plant growth and enhancing overall crop efficacy.

Nitrogen uptake and content in shoots

The findings indicate that N absorption in wheat shoots significantly increased during the tillering, pre-anthesis, and dough stages, attaining peak levels with the application of 120 kg N + 30 kg S (13.91, 34.80, 41.50, and 39.89 kg ha^{-1}, respectively). This is due to the essential function of N in chlorophyll synthesis, photosynthesis, and protein synthesis, which are required for continuous growth and biomass accumulation during these pivotal developmental stages (13). Enhanced N absorption recorded at the dough stage indicates that it facilitate both vegetative growth and essential reproductive stages of wheat development, hence leading to improved grain yield. The control treatment (0 kg N, 0 kg S) exhibited the lowest N uptake at all development stages (1.44, 13.18, 9.26, and 8.60 kg ha^{-1}), indicating the detrimental effects of nutrient limitation on wheat growth. The deficiency of sufficient N and S in the control resulted in inadequate biomass production and inhibited plant growth, especially during critical phases such as pre-anthesis and the dough stage, when nutrient requirements are at their highest as showed in Fig. 1. The results are align with the findings of (14).

Nitrogen uptake by grain and nutrient content in grain

The uptake of N by grain showed significant enhancements with higher applications of N and S. The maximum N uptake in grains at maturity (152.36 kg ha^{-1}) occurred with application of 120 kg N + 30 kg S, while the

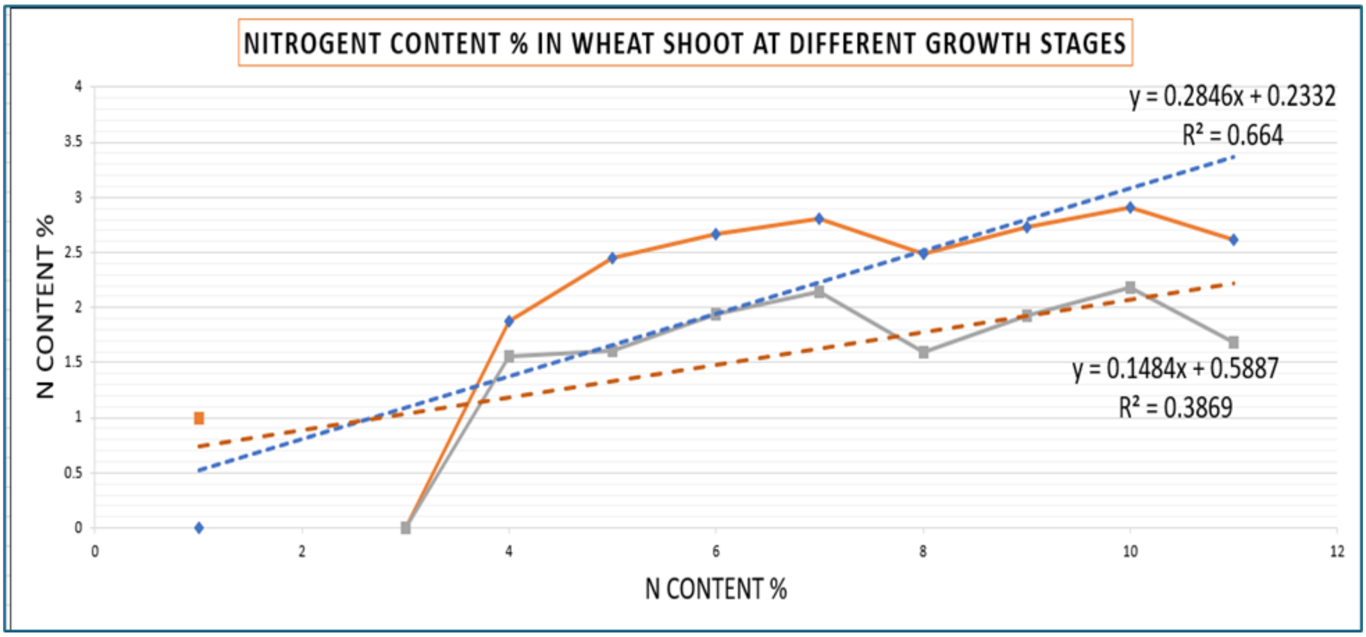

Fig. 1. Response curves of N fertilization to N content % in shoot at various growth stages of wheat. The trend shown that (a second-degree polynomial equation ($y = a + bx + cx^2$) of N fertilization at dough stage was maximum and diminish curve obtained at maturity stage. Orange dash line representing N content % in shoot at tillering stage, blue dash line representing N content % in shoot at pre anthesis stage, orange straight line shown that N content % in shoot at dough stage and grey straight line indicating S content % in shoot at maturity stage.

control exhibited the minimum uptake (43.69 kg ha^{-1}). The increase in grain N absorption at elevated nitrogen and S levels aligns with nitrogen's function in protein synthesis, which is directly related to grain quality and yield. Moreover, S has a synergistic function in improving N efficiency, as it is crucial for amino acid and protein synthesis, hence aiding nitrogen assimilation in the plant (15). The statistical equivalence of 40 kg and 80 kg N treatments regarding grain N levels at 0 kg, 15 kg, and 30 kg S indicates that, up to a specific threshold, moderate N administrations may produce comparable N absorption reactions in the grain (16). The markedly enhanced performance of 120 kg N in grain and shoot absorption across all S levels (0 kg, 15 kg, and 30 kg S) suggests that the supplementary N was utilized more effectively when combined with S, especially at 30 kg S, where nutrient requirements peak during essential growth stages. The results are in accordance with the findings of in wheat (17).

Sulphur uptake and content in wheat

The addition of 40 kg, 80 kg, and 120 kg N markedly enhanced S content and absorption in wheat shoots compared to the control (0 kg N). The maximum S absorption was continuously recorded with the application of 120 kg N + 30 kg S (3.17, 6.91, and 8.36 kg ha^{-1} at the tillering, pre-anthesis, and dough stages, respectively). This trend underscores the significant synergistic impact of increased nitrogen levels on S metabolism. Nitrogen is essential for boosting vegetative growth and improving S consumption in plants, thereby enhancing total nutrient efficiency and absorption at all S levels such as 0 kg, 15 kg, and 30 kg S (18). This indicates that as N levels rise, the plant's requirement and ability to absorb S also increase, further illustrating the interdependent functions of these nutrients in wheat growth and development. A study of S uptake among the various S treatments (0 kg, 15 kg, and 30 kg S) demonstrated a distinct benefit associated with increased S application (18). The maximum S uptake was observed with 120 kg N + 30 kg S, whereas the minimum (0.24, 1.05, and 0.92 kg ha^{-1} at the tillering, pre-anthesis, and dough stages, respectively) was recorded in the control group, as shown in Fig. 2. This mismatch highlights the essential function of S in combination with N to promote plant growth, as S is an essential component of amino acids such as cysteine and methionine, which are crucial for protein synthesis and plant metabolism (19). This outcome indicates that, in the absence of S supplementation, the advantages of elevated N levels in enhancing absorption. Sulphur must be present in sufficient quantities to completely achieve the advantages of N fertilization (20). The substantial enhancement in nutrient absorption is due to the synergistic interaction of N and S, which collectively promote intense plant growth, grain development, and enhanced nutrient allocation to the grain. Nitrogen promotes vegetative development and protein synthesis, but S improves N utilization efficiency, thus facilitating the translocation of nutrients to the grain, which is essential for attaining increased yields and superior grain quality (21).

Production efficiency of N and S

The results of this study highlight the complex interplay between N and S in wheat cultivation. The superior N production efficiency in the 120 kg N treatments indicates that it is a limiting factor for yield maximization, while S serves a complementary role, especially at reduced N levels, as evidenced by the comparatively high N production efficiency in the 40 kg N + 30 kg S treatment (22).

The reduction in S production efficiency with higher levels indicates that its application must be carefully regulated to prevent diminishing returns. Excessive S treatment, especially in combination with elevated N levels, may not generate proportionate improvements and could diminish nutrient usage efficiency. For optimum results, the N:S ratio should be 10-15:1 for most of cereal crops. Applying N without S may widen a crop's N:S ratio

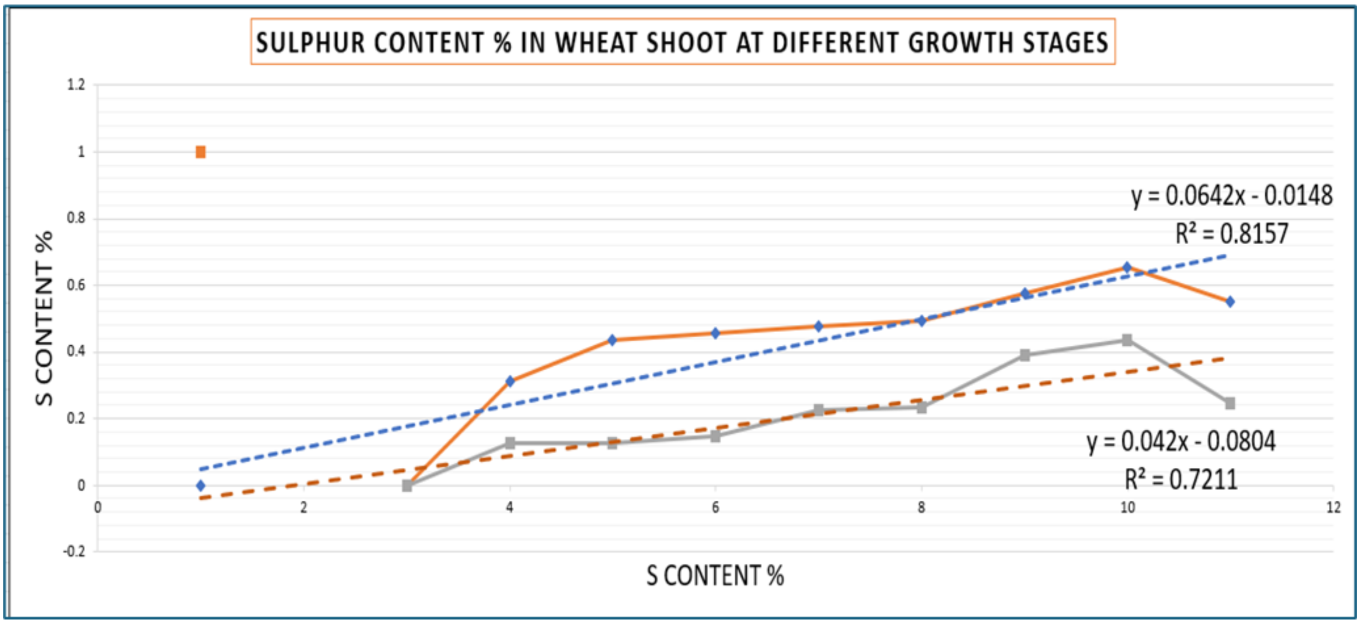

Fig. 2. Response curves of S fertilization to S content % in shoot at various growth stages of wheat. The trend shown that (a second-degree polynomial equation ($y = a + bx + cx^2$) of S fertilization at dough stage was maximum and diminish curve obtained at maturity stage. Orange dash line representing S content % in shoot at tillering stage, blue dash line representing S content % in shoot at pre anthesis stage, orange straight line shown that S content % in shoot at dough stage and grey straight line indicating S content % in shoot at maturity stage.

and actually induce a S deficiency (22). This highlights the significance of balanced nutrient management, wherein both N and S are administered in optimal quantities to enhance their synergistic benefits and prevent waste. The reduced production efficiency at 40 kg N + 0 kg S highlights the essential function of S in enhancing N usage efficiency, especially under conditions of restricted supplies. In situations when N availability is limited, S supplementation is essential for facilitating effective nutrient absorption and maximizing output (23).

Response of N and S

The data indicated that by applying 40 kg N and 30 kg S, the crop showed better response to N. By decreasing levels of N and increasing levels of S, greater production efficiency was recorded as compared to 80 kg Nand 120 kg N. The highest response of N (36.11 kg) yield increased by applying 40 kg N + 30 kg S with 26.98 kg yield (24). The response of S mean data indicated that the response of S recorded maximum at lower level of S 15 kg and decreased as levels progressed. The highest response of S (82 kg yield increased) was recorded in 120 kg N + 15 kg S whereas lowest response of S (48.14 kg) recorded in 40 kg N + 30 kg S. The results are in conformity with the findings of the previous study (25).

NUE and SUE

The maximum NUE of 91.31% was recorded in the treatment that received 120 kg of N and 30 kg of S. The elevated NUE signifies that the incorporation of increased N and S concentrations enabled the crop to efficiently assimilate and utilize the administered nitrogen, resulting in enhanced production and improved nitrogen use efficiency. The treatment with 80 kg N + 30 kg S exhibited a NUE of 90.56%, indicating that a somewhat reduced N delivery rate, combined with adequate S (30 kg), sustained a high NUE. The elevated NUE observed in these treatments underscores the significance of S in improving N metabolism and absorption. The maximum SUE of 84.10% was observed in the treatment 120 kg N + 30 kg S, while 80 kg N + 30 kg S exhibited an SUE of 81.56%. These results demonstrate that elevated N levels, in conjunction with sufficient S, enhance the plant's efficiency in utilizing S. The high SUE in these treatments indicates that the application of 30 kg of S was ideal for facilitating N absorption and improving overall plant metabolism. The results are in conformity with the findings of the previous study (26).

Conclusion

The research clearly indicates that N and S fertilization levels significantly influence nutrient absorption in wheat, with the combination of 120 kg N and 30 kg S yielding the highest N uptake in both shoots and grain across all growth stages. The findings indicate that effective management of nitrogen and Sulphur is essential for enhancing nutrient efficiency, improving grain quality, and ensuring sustainable wheat production. This research provides critical insights for formulating fertilization strategies that improve crop output while addressing the need for effective nutrient management in agricultural systems. The study concludes that nitrogen production efficiency peaks at elevated nitrogen levels, especially when S is present, whereas S production efficiency declines as S and N levels rise. These findings provide critical insights for formulating nutrient management strategies that enhance N and S utilization in wheat agriculture. By carefully balancing N and S inputs, farmers can achieve increased production efficiency, improve crop yields, and mitigate the negative environmental impacts of excessive fertilizer use. This study highlights that balanced nitrogen (120 kg ha^{-1}) and sulphur (30 kg ha^{-1}) fertilization significantly enhances nutrient uptake, grain quality, and production efficiency in wheat. Future research should focus on the long-term impacts on soil health, microbial diversity, and strategies to enhance environmental sustainability in fertilization practices.

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Authors Contributions

GPS prepared the research plan and analysis. AS and SS provided guidelines during the research work and research methodology. ZAS, P, AC and IF helped with writing and proofreading of the manuscript.

Compliance with Ethical Standards

Conflict of interest: The authors do not have any conflict of interest to declare.

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