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Agro-economic evaluation of sulphur fertilisation of wheat (*Triticum aestivum*) under wheat–rice (*Oryza sativa*) cropping sequence in Indo-Gangetic plains

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ABSTRACT

The present field experiment was aimed to study the agro-economic evaluation of sulphur fertilisation on growth attributes, yield, production and monetary efficiency of wheat (*Triticum aestivum* L.) in wheat–rice (*Oryza sativa* L.) cropping sequence conducted during the winter (*rabi*) seasons of 2023–24 and 2024–25 at the Research Farm of ICAR-Indian Agricultural Research Institute, New Delhi. The experiment was conducted in randomised complete block design (RCBD) with three replications consisting of five sulphur levels, viz. 0, 15, 30, 45 and 60 kg S/ha. Results showed that the application of sulphur significantly enhanced growth attributes such as height, tiller, dry matter accumulation (DMA), yield and monetary efficiency. In 2023–24, 45 kg S/ha improved plant height by 12.4%, tillers/m² by 59.7% and DMA by 80.2% over the control. Similarly, in 2024–25, 30 kg S/ha increased plant height by 10.6%, tillers by 66.6% and DMA by 80.7%. Physiological traits like LAI, SPAD and NDVI were also enhanced. LAI rose by 50.8% in 2023–24 and 53.0% in 2024–25 with 30 kg S/ha, while SPAD increased by 14.6% and 16.8% and NDVI by 17.7% and 20.2% over the control in respective years. Grain yield increased by 43% (2023–24) and 38.4% (2024–25) with 45 and 30 kg S/ha, respectively. Agronomic efficiency peaked at 30 kg S/ha in 2023–24 (56.3 kg grain/kg S) and 15 kg S/ha in 2024–25 (95.3 kg grain/kg S). Production efficiency increased by 42.9% in 2023–24 and 38.3% in 2024–25 with 45 and 30 kg S/ha over the control, respectively. Sulphur fertilisation at 30–45 kg/ha consistently improved growth, yield and profitability, with 30 kg/ha being the most efficient rate.

Keywords: Leaf area index, Monetary efficiency, NDVI, Nutrient management, SPAD, Wheat productivity

Wheat (*Triticum aestivum* L.) is a globally significant food crop, with yield enhancement and quality improvement being long-standing objectives in breeding programmes to fulfil the nutritional demands of an expanding population (Liu *et al.* 2022, Mandi *et al.* 2024). It's the most widely cultivated cereal crops, contributing significantly to global food security by providing approximately 20% of the total dietary calories and proteins for the world's population (Liu *et al.* 2022, Dawar *et al.* 2022). In India, wheat occupies over 31 mha and is a staple in the diet of millions, particularly in the rice–wheat cropping systems of the Indo-gangetic Plains (Ram *et al.* 2014, Mandi *et al.* 2022). Among the essential nutrients, sulphur has emerged as a critical macronutrient required for optimal wheat growth and development. Sulphur, an integral component of essential amino acids such as cysteine, methionine and vitamins and coenzymes plays a key role in protein synthesis, enzyme activation and photosynthesis (Shivay *et al.* 2014, Ram *et al.* 2018, Liu *et al.* 2022). However, in the last few decades, reduced industrial sulphur emissions, increased use of sulphur-free fertilisers like urea and DAP and intensive cropping have led to widespread sulphur deficiencies in agricultural soils, particularly in cereal-based systems (Shivay *et al.* 2014, Dhillon *et al.* 2019). Recent surveys and studies have shown that over 40% of soils in India are sulphur-deficient, while another 35% are potentially deficient (Ram *et al.* 2018 and 2021). Multiple field experiments have demonstrated the positive impact of sulphur application on wheat growth, yield and grain quality (Dawar *et al.* 2022, Sharma *et al.* 2023).

In terms of grain quality, sulphur fertilisation plays a crucial role in the synthesis of storage proteins, particularly glutenin and gliadin, which are key determinants of dough elasticity and baking performance (Mandi *et al.* 2024). Studies have reported that sulphur application can improve the grain protein content by 2–3% and significantly increase the glutenin-to-gliadin ratio, enhancing wheat's functional quality (Liu *et al.* 2022, Mandi *et al.* 2024). Beyond yield and protein content, sulphur fertilisation influences several other parameters including semolina yield, β-carotene,

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zinc and iron concentration in grains - traits particularly important in durum wheat production for pasta making (Ram *et al.* 2014, Mandi *et al.* 2022). Although several studies have established the positive impact of sulphur on wheat growth, limited information exists on its agro-economic efficiency under wheat–rice systems in sulphur-deficient Inceptisols in the Indo-Gangetic plains. The present study was undertaken following objectives, to evaluate the effect of sulphur fertilisation on the growth, yield, profitability and nutrient use efficiency of wheat. The goal is to develop a balanced and sustainable nutrient management strategy that not only enhances productivity but also improves the nutritional profile and quality of wheat grains.

MATERIALS AND METHODS

The field experiment was conducted during winter the (*rabi*) seasons of 2023–24 and 2024–25 at the Research Farm of ICAR-Indian Agricultural Research Institute (28.4°N and 77.1°E with an altitude of 228.61 m amsl), New Delhi. The experimental site experiences a semi-arid subtropical climate, receiving ~1105 mm annual rainfall, more than 80% generally occurs during south-west monsoon season (July–September) and ~850 mm pan evaporation. The soil (0–15 cm) was sandy clay loam (inceptisol) with 50.91% sand, 24.69% silt and 25.01% clay, *p*H 7.99, 0.51% organic carbon and available nutrients, N (94.8 kg/ha), P (6.58 kg/ha), K (273.64 kg/ha), S (2.36 ppm), Fe (2.21 ppm) and Zn (1.38 ppm). The experiment was laid-out in randomised complete block design (RCBD) with three replications. The treatment consisted of five sulphur levels, viz. 0, 15, 30, 45 and 60 kg S/ha. The unit plot size was 20 m^2. Source of sulphur in experiment was water dispersible granules of micronised sulphur (WDGMS) containing 80% sulphur (only S sources more efficient than other because micronised form). The experimental land prepared for wheat involved 2–3 passes with a cultivator followed by rotavator to create a fine seedbed. Spring wheat variety HD 3086 was sown on 24 and 7 November in 2023 and 2024–25, respectively, at a spacing of 22.5 cm × 10 cm using a seed rate of 60 kg/ha, by seed drill. The recommended dose of NPK (150:60:40 kg/ha) along with sulphur was applied in both years. Half of the nitrogen (N) and the full dose of phosphorus (P), potassium (K) and sulphur (S) were applied basally, while the remaining N was split between the active tillering and panicle initiation (PI) stages. Fertiliser sources included GNCU, DAP, MOP and WDGMS, supplying NPK and S, respectively.

All the necessary data on crop growth were recorded by following the standard procedures. In addition, chlorophyll content was measured non-destructively using a SPAD-502 Plus meter. Readings were taken from the middle of fully expanded leaves at 30, 60 DAS and flowering (Ram *et al.* 2018). The NDVI was assessed using a handheld GreenSeeker® sensor. The leaf area was recorded at 30, 60 DAS and flowering stage. The area of fresh green leaves for each treatment was measured by using leaf-area meter (Model LICOR 3000, USA). Leaf-area index (LAI) was computed as per the procedure described by Evans (1972):

$$\text{Leaf Area Index (LAI)} = \frac{\text{Total leaf area (cm}^2\text{)}}{\text{Ground area (cm}^2\text{)}} \quad (1)$$

Production efficiency (kg/ha/day) measures the grain yield obtained when it is distributed over the duration and is calculated as:

$$\text{Production efficiency} = \frac{\text{Grain yield of the crop in kg/ha}}{\text{Duration of the crop in days}} \quad (2)$$

Monetary efficiency (₹/ha/day) calculates the net returns of the crop which is distributed over a crop growing period using the given formula:

$$\text{Monetary efficiency} = \frac{\text{Net returns (₹/ha)}}{\text{Duration of the crop in days}} \quad (3)$$

The variance was conducted for growth attributes, yield components and yield of spring wheat using the standard analysis of variance (ANOVA) technique (Gomez and Gomez 1984). When the F-value was significant at the $p<0.05$ level, treatment means were compared using Duncan's Multiple Range Test (DMRT) as described by Steel and Torrie (1960). Data were analysed following standard procedures using SAS software (version 9.1 SAS Institute 2004). The response to sulphur was studied by fitting different regression response equations for grain yield. A Pearson's correlation coefficient matrix was constructed among the key growth attributes, yield and efficiency of spring wheat work out using the data analysis tool pack of Microsoft Excel (2010).

RESULTS AND DISCUSSION

Growth attributes: The application of sulphur had a marked impact on plant height at harvest in both the seasons (2023–24 and 2024–25) (Table 1). In 2023–24, plant height increased progressively with sulphur doses, compared to the control (0 kg S/ha), the 30 and 45 kg S/ha treatments recorded increase of 10.63% and 12.39%, respectively. A similar trend was observed in 2024–25, where the highest plant height (112.58 cm) was noted at 30 kg S/ha, which was 10.61% greater than control treatments. However, the difference among 30, 45 and 60 kg S/ha in 2024–25 was not statistically significant. The increase in plant height with sulphur application may be attributed to enhanced cell division, elongation and chlorophyll synthesis, nutrient uptake and photosynthetic efficiency which collectively promoted vegetative growth (Ram *et al.* 2014, Mandi *et al.* 2022). Sulphur plays a crucial role in the formation of essential amino acids (cysteine and methionine) and coenzymes, contributing to protein synthesis and enzymatic activity (Liu *et al.* 2022, Dhillon *et al.* 2019).

Tillering of wheat was significantly influenced by sulphur application in both years (Table 1). In 2023–24, the highest tiller count was observed in the 45 kg S/ha (489.30 tillers/m²), representing a 59.73% increase over control treatment. Other treatments 15 kg S/ha (18.27%),

Table 1 Effect of sulphur levels on plant height, tillers/m^2 and DMA of wheat at harvest stage

Treatments	Plant height (cm)		Tillers/m^2		DMA (g/m^2)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Control	98.4^B±0.71	101.7^B±0.30	306.4^C±5.83	298.4^D±1.76	997.5^D±12.70	991.5^E±4.39
15 kg S/ha	102.6^B±0.26	111.2^A±1.93	362.4^B±4.56	478.4^B±3.86	1192.8^C±14.69	1742.8^B±12.69
30 kg S/ha	108.8^A±0.92	112.5^A±0.62	474.1^A±7.45	497.1^A±8.23	1651.6^B±25.26	1791.6^A±25.13
45 kg S/ha	110.6^A±1.59	109.3^A±0.83	489.3^A±5.64	443.3^C±5.27	1797.8^A±35.14	1637.8^C±9.74
60 kg S/ha	109.0^A±0.41	108.7^A±1.57	458.9^A±4.46	432.9^C±5.15	1571.7^B±20.03	1591.7^D±7.06

DMA, Dry matter accumulation; Means followed by the same letters within a column do not differ significantly (p≤0.05) according to DMRT.

30 kg S/ha (54.78%) and 60 kg S/ha (49.80%), also showed substantial improvement in wheat tillering. In 2024–25, maximum tillers were recorded in the 30 kg S/ha (497.1 tillers/m²), which was 66.59% higher than the control while 15, 45 and 60 kg S/ha also increased tillers by 60.31%, 48.53% and 45.06%, respectively. These results clearly indicate that sulphur application significantly boosts tillering capacity. This improvement can be attributed to sulphur role in nitrogen metabolism and photosynthetic allocation, which supports the development of productive tillers (Palsaniya *et al.* 2009, Liu *et al.* 2022, Dawar *et al.* 2022). Enhanced metabolic activity due to optimal sulphur availability likely contributed to greater shoot proliferation and sink strength (Shivay *et al.* 2014, Ram *et al.* 2018).

Dry matter accumulation (DMA) followed a trend similar to plant height and tillering, with a pronounced positive response to sulphur fertilisation (Table 1). In 2023–24, the 45 kg S/ha produced the highest DMA (1797.84 g/m²), which was 80.24% higher than the control. In 2024–25, maximum DMA was recorded at 30 kg S/ha (1791.6 g/m²), an 80.65% increase over control. The 15, 45 and 60 kg S/ha also showed significant enhancements of 75.70%, 65.19% and 60.49%, respectively. The increased dry matter accumulation can be explained by improved nutrient assimilation, particularly nitrogen uptake, in the presence of adequate sulphur (Ram *et al.* 2014, Mandi *et al.* 2024). Sulphur enhances rubisco activity and protein synthesis, ultimately improving photosynthetic efficiency and biomass production (Fuentes-Lara *et al.* 2019, Li *et al.* 2020, Dawar *et al.* 2022).

LAI, SPAD and NDVI value: Sulphur application significantly influenced the Leaf Area Index (LAI) of wheat in both 2023–24 and 2024–25 (Table 2). In 2023–24, the LAI increased from 3.95 in the control (S_0) to 5.82, 5.95, and 5.79 in 30, 45 and 60 kg S/ha, respectively, representing increases of 47.34%, 50.63% and 46.58%, respectively over control (No S). Sulphur application @15 kg S/ha showed a modest increase of 12.4%. In second year (2024–25), the highest LAI (6.09) was recorded at 30 kg S/ha, registering a 52.78% increase over the control. The treatments 15, 45 and 60 kg S/ha recorded increases of 49.24%, 49.49% and 45.73%, respectively, suggesting that sulphur levels ≥30 kg S/ha substantially enhanced canopy development. Improved LAI under sulphur fertilisation reflects enhanced leaf expansion and increased photosynthetic surface area. Sulphur plays a key role in protein synthesis and chloroplast development, promoting better canopy structure (Dhillon *et al.* 2019, Mandi *et al.* 2022, Dawar *et al.* 2022).

The SPAD (Soil-Plant Analysis Development) chlorophyll meter readings, which indicate chlorophyll content and indirectly nitrogen status, were significantly affected by sulphur levels (Table 2). In 2023–24, SPAD values ranged from 38.93–44.67, with 15, 30, 45 and 60 kg S/ha result in the increases of 3.34%, 14.44%, 14.75% and showed increase 12.99%, respectively, over the control. In 2024–25 a similar pattern emerged, SPAD values increased

Table 2 Effect of sulphur levels LAI, SPAD and NDVI value of wheat at flowering stage

Treatments	LAI		SPAD value		NDVI value	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Control	3.95^C±0.06	3.98^C±0.04	38.9^B±0.74	38.3^B±0.66	0.79^B±0.013	0.79^C±0.008
15 kg S/ha	4.44^B±0.05	5.94^{AB}±0.03	40.2^B±0.66	44.2^B±0.55	0.88^B±0.008	0.93^A±0.009
30 kg S/ha	5.82^A±0.05	6.09^A±0.08	44.5^A±0.26	44.7^A±0.89	0.93^A±0.004	0.95^A±0.01
45 kg S/ha	5.95^A±0.02	5.95^{AB}±0.09	44.6^A±0.47	44.0^A±0.37	0.95^A±0.015	0.91^A±0.003
60 kg S/ha	5.79^A±0.08	5.79^B±0.12	43.9^A±0.27	43.1^A±0.55	0.89^A±0.0015	0.90^B±0.002

LAI, Leaf area index; SPAD, Soil Plant Analysis Development; NDVI, Normalised Difference Vegetation Index; Means followed by the same letters within a column do not differ significantly (p≤0.05) according to DMRT.

from 38.33–44.75, which was a 16.75% improvement. Treatments 15, 30, 45 and 60 kg S/ha recorded increases of 13.33%, 14.34%, 14.97% and 12.67%, respectively, highlighting enhanced chlorophyll formation with sulphur supply. Sulphur is essential for the synthesis of Fe-S clusters and thylakoid proteins involved in photosynthesis (Mandi *et al.* 2022, Sharma *et al.* 2023). Increased SPAD readings indicate improved chlorophyll biosynthesis and nitrogen utilisation efficiency, which are often limited under sulphur-deficient conditions (Tondan 2011).

NDVI value, an indicator of plant vigour and green biomass, was also significantly enhanced by sulphur application (Table 2). In 2023–24, NDVI ranged from 0.79 to 0.95, representing 20.25% increment where 15 and 60 kg S/ha showed increases of 11.39% and 12.66%, respectively, over control. In 2024–25, the trend continued, NDVI value rose from 0.79 to 0.95, a 20.25% improvement where 15, 45 and 60 kg S/ha showed increases of 17.72%, 15.19% and 13.92%, respectively. The higher NDVI values in 30 and 45 kg S/ha treatments suggest improved vegetative vigour and canopy greenness. Higher NDVI values correlates with improved crop nitrogen status, chlorophyll content and biomass accumulation (Tondan 2011, Shivay *et al.* 2014, Ram *et al.* 2018). Sulphur application likely improved photosynthetic efficiency and delayed senescence, resulting in greener and more vigorous plants at flowering (Fuentes-Lara *et al.* 2019, Dawar *et al.* 2022).

Productivity: Sulphur application significantly improved wheat grain yield across both years (Table 3). In 2023–24, grain yield increased from 4.10–5.86 t/ha, reflecting a 43.0% increase over the control. The treatments 15, 30 and 60 kg S/ha also recorded yield increase of 20.24%, 41.22% and 38.78%, respectively. In 2024–25, the highest grain yield (5.95 t/ha) was observed at 30 kg S/ha, which was 38.37% higher than the control where 15, 45 and 60 kg S/ha, showed respective increase of 33.26%, 29.77% and 26.51%, indicating that sulphur application consistently enhances grain productivity. The yield improvement under sulphur fertilisation is attributed to enhanced nitrogen use efficiency, better source-sink relationship and greater biomass accumulation (Fuentes-Lara *et al.* 2019, Sharma *et al.* 2023). However, yield declined slightly at the highest sulphur rate (60 kg S/ha) in 2024–25, likely due to nutrient imbalance or saturation effects (Ram *et al.* 2018, Shivay *et al.* 2014, Mandi *et al.* 2024–5).

Harvest index (HI) indicates grain-straw ratio and partitioning efficiency of assimilates towards economic yield (Table 3). In 2023–24, HI improved from 40.88–45.75, an increase by 11.91% where 15, 30 and 60 kg S/ha showed increases of 6.93%, 11.51% and 10.92%, respectively. In 2024–25, HI increased from 42.03–44.20, a 5.16% increase, while 15, 45 and 60 kg S/ha showed more modest grains. The highest ratio in both years was consistently recorded at 30–45 kg S/ha, suggesting that sulphur at these levels promoted efficient assimilate allocation to grains. Improved HI is indicative of a physiological shift favouring grain production, often supported by improved availability of photosynthates and hormonal balance under optimal sulphur conditions (Tandon 2011, Sharma *et al.* 2023).

Application of 30 kg S/ha consistently resulted in superior values of tillers, DMA, LAI, SPAD, NDVI, grain yield and efficiency indices across both years, indicating it as the optimum sulphur dose for enhancing physiological performance and canopy development at the flowering stage in the wheat–rice system. Higher doses (45–60 kg S/ha) showed no additional benefit and occasionally reduced performance, likely due to nutrient imbalance. Thus, balanced sulphur nutrition at 30 kg/ha effectively supports chlorophyll synthesis, leaf expansion and canopy reflectance, contributing to improved biomass accumulation and yield in sulphur-deficient soils in wheat–rice cropping sequence (Ram *et al.* 2014, Mandi *et al.* 2022, Sharma *et al.* 2023).

Agronomic efficiency: Agronomic efficiency (AE), defined as the grain yield increase per unit of sulphur applied (kg grain/kg S), varied significantly ($p<0.05$) across treatments and years, reflecting the crop responsiveness to different levels of sulphur application (Table 3). In 2023, the highest AE was observed at the 30 kg S/ha level, recording 56.33 kg grain/kg S, closely followed by 15 kg S/ha at 55.33 kg grain/kg S. These values indicate that initial sulphur supplementation in sulphur-deficient soils led to a sharp yield increase with high input-use efficiency. However, AE declined with further increases in sulphur rate: 39.11 kg/kg S at 45 kg S/ha and 26.50 kg grain/kg S at 60 kg S/ha, indicating diminishing returns. This drop in efficiency beyond the 30 kg S level may be attributed

Table 3 Effect of sulphur levels on yield, harvest index and agronomic efficiency of wheat

Treatments	Grain yield (t/ha)		Harvest index (%)		Agronomic efficiency (kg grain /kg S applied)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Control	4.10^{C}±0.02	4.30^{D}±0.096	40.88^{B}±0.81	42.03^{B}±0.50	-	-
15 kg S/ha	4.93^{B}±0.02	5.73^{AB}±0.057	43.71^{AB}±0.38	43.47^{AB}±0.72	55.33^{A}±0.66	95.33^{A}±0.85
30 kg S/ha	5.79^{A}±0.04	5.95^{A}±0.065	45.59^{A}±0.74	44.20^{A}±0.28	56.33^{A}±0.23	55.00^{B}±0.58
45 kg S/ha	5.86^{A}±0.10	5.58^{BC}±0.069	45.75^{A}±0.56	42.95^{AB}±0.69	39.11^{B}±0.49	28.44^{C}±0.34
60 kg S/ha	5.69^{A}±0.03	5.44^{C}±0.085	45.34^{A}±0.92	42.50^{AB}±0.36	26.5^{C}±0.33	19.00^{D}±0.26

Means followed by the same letters within a column do not differ significantly ($p\leq0.05$) according to DMRT.

to a saturation point where the plant's sulphur demand is already met and additional supply does not translate into proportional yield gains.

In 2024–25, a similar trend was observed but with greater magnitude of AE, particularly at lower sulphur rates. The 15 kg S/ha exhibited the highest AE at 95.33 kg grain/kg S, which was significantly higher than in 2023–24, suggesting improved responsiveness of the crop possibly due to residual effects or more favourable growing conditions. At 30 kg S/ha, AE dropped to 55.00 kg grain/kg S, still a reasonably efficient level. However, AE declined steeply at higher doses, reaching 28.44 kg grain/kg S at 45 kg S/ha and only 19.00 kg grain/kg S at 60 kg S/ha. The findings showed that agronomic efficiency of sulphur decreases when application exceeds a certain threshold, aligning with the law of diminishing returns. Although sulphur is essential for physiological and biochemical functions, excessive application can lower uptake efficiency and cause economic losses without yield benefit. The study indicates that 15–30 kg S/ha is the optimal range for maximising yield and nutrient efficiency in wheat. Notably, 15 kg S/ha was the most efficient in 2024–25, possibly due to improved soil fertility (residual effect). In contrast, rates above 30 kg S/ha reduced AE, emphasising the need for site-specific sulphur management to achieve both productivity and sustainability (Dhillon *et al.* 2019, Mandi *et al.* 2024).

Production and economic efficiency: Sulphur application showed a clear positive effect on wheat production efficiency (PE) in both years (Fig. 1). In 2023–24, PE increased from 30.37 kg grain/ha/day under control to a peak of 43.41 kg grain/ha/day at 45 kg S/ha, registering a 43% increment. Other treatments with 15, 30 and 60 kg S/ha also showed significant improvements of 20.2%, 41.2% and 38.8%, respectively, over control. In 2024–25, maximum PE was recorded at 30 kg S/ha (42.81 kg grain/ha/day), which was 38.3% higher than the control. 15 kg S/ha and 45 kg S/ha also performed well with 41.22 and 40.14 kg grain/ha/day, whereas PE declined slightly at 60 kg S/ha (39.14 kg grain/ha/day). The results suggest that 30–45 kg S/ha optimally enhances PE by improving physiological efficiency, canopy growth and grain filling duration. A slight drop at higher levels (60 kg S/ha) implies diminishing returns due to possible nutrient imbalance or saturation (Ram *et al.* 2018, Mandi *et al.* 2024).

Monetary efficiency (ME), expressed as ₹ earned/ha/day, improved significantly with sulphur application in both years, reflecting the economic benefit of increased grain productivity relative to time and input use (Fig. 2). In 2023–24, ME increased from 599.4 ₹/ha/day under the control to a maximum of 906.5 ₹/ha/day at 45 kg S/ha, representing a 46.9% increment. Treatments (kg S/ha), 15, 30 and 60 kg S /ha also showed substantial gains of 19.9%, 46.2% and 40.7%, respectively, over the control. The highest efficiency at 45 kg S/ha in 2023–24 indicates better economic returns during that season under higher S levels. In second year (2024–25), ME was generally higher across treatments, with the maximum recorded at 30 kg S/ha (1017.6 ₹/ha/day), which was 35% higher than the control. Treatments, 15 and 45 kg S/ha showed comparable ME values of 985 and 938.3 ₹/ha/day, respectively, while 60 kg S/ha remained slightly lower at 902.2 ₹/ha/day. The decline in ME beyond 30 kg S/ha suggests a reduction in economic returns per unit of time at higher sulphur inputs.

Sulphur application significantly enhanced monetary efficiency in wheat production. Treatment 30 kg S/ha emerged as the most economically efficient, especially in 2024–25, delivering the highest return per hectare per day due to residual effect of sulphur. While 45 kg S/ha showed the highest ME in 2023–24, the reduced efficiency at 60 kg S/ha across both years suggests that over application of sulphur leads to diminishing economic returns. Therefore, 30–45 kg S/ha appears to be the optimum economic range for maximising profitability and time-based efficiency in wheat under the tested conditions (Shivay *et al.* 2014, Ram

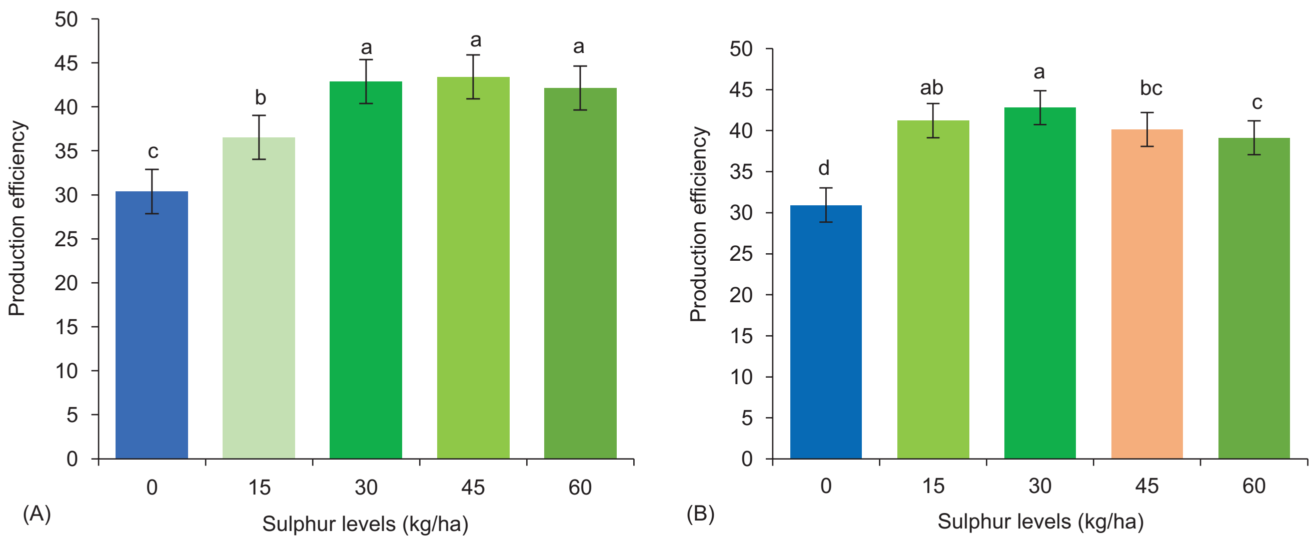

Fig. 1 Effect of sulphur levels on production efficiency (kg grain/ha/day) of wheat in 2023–24 (A) and 2024–25 (B). Means followed by the same letters within a column do not differ significantly ($p \leq 0.05$) according to DMRT.

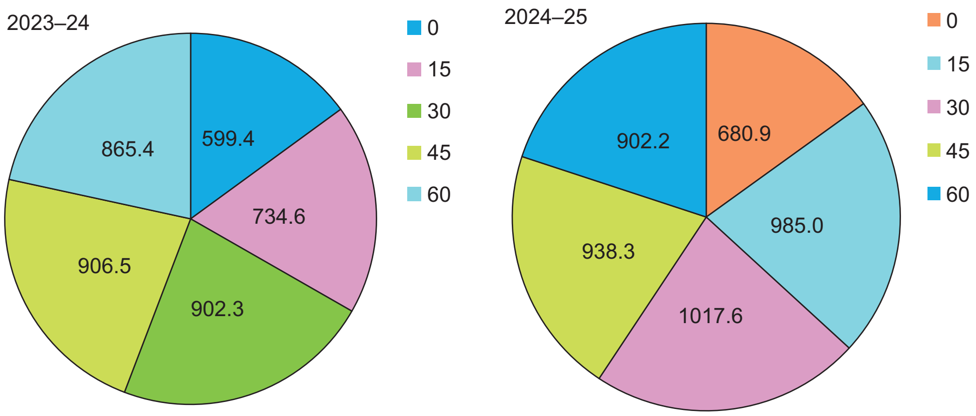

Fig. 2 Effect of sulphur levels @0, 15, 30, 45 and 60 are levels of sulphur (kg/ha) on monetary efficiency (₹/ha/day) of spring wheat.

systems. The regression coefficient (R^2) was significantly influenced by sulphur fertilisation rate. The relationship between grain yield in 2023–24 (R^2 =0.98) and 2024–25 (R^2 =0.85) of spring wheat and sulphur fertilisation rate was highly significant and showed quadratic response (Fig. 3). The regression graph also showed that increasing the level of sulphur beyond the optimum range (15–30 kg/ha) reduced the crop

et al. 2016, Mandi *et al.* 2022, Sharma *et al.* 2023).

Correlation coefficient and regression analysis: The correlation coefficient analysis (Table 4) of various traits of wheat revealed significant positive correlation (***, p<0.001; **, p<0.01; *, p<0.5) relationships among growth components, yield and efficiency. Growth attributes such as plant height, tillers, dry matter accumulation, leaf area index, SPAD and NDVI value showed a significantly (p<0.05) positive correlation with grain yield and monetary efficiency, respectively. Furthermore, grain yield and grain-straw ratio (G:S) had significantly positively correlation with TH, DMAH, LAIF, SPADF, NDVIF, production and ME. Additionally, agronomic, production and ME showed a significantly positive correlation with TH, DMAH, LAIF, SPADF, NDVIF and GY.

Above findings suggest that selecting for traits such as higher dry matter accumulation, leaf area index and chlorophyll content can indirectly enhance yield and profitability through their positive linkage with agronomic and economic efficiency. The strong interdependence among these traits emphasises the value of integrated crop management practices that simultaneously optimise growth, resource use and yield outcomes in wheat production

response.

The results clearly demonstrate that sulphur application significantly enhances wheat performance in terms of growth, yield, agronomic efficiency and monetary efficiency. Across both seasons (2023–24 and 2024–25), application of 30–45 kg S/ha markedly improved height, tillers, DMA, physiological indices such as LAI, SPAD, NDVI value, grain yield and monetary efficiency. These improvements translated into substantial yield gains - up to 43% in 2023–24 (45 kg S/ha) and 38% in 2024–25 (30 kg S/ha) over the control. Agronomic efficiency, production efficiency and monetary efficiency followed a similar pattern, with the highest values observed at 15–30 kg S/ha, beyond which returns diminished. The sharp decline in efficiency beyond this range suggests that excessive S does not contribute proportionally to yield and may even reduce input-use efficiency. Among all treatments, 30 kg S/ha consistently provided the most balanced outcomes, optimising both biological and economic performance. It resulted in high grain yield, physiological vigour and efficient resource conversion (both kg grain/ha/day and ₹/ha/day). It is thus concluded that sulphur application in the range of 30–45 kg/ha is recommended for wheat under sulphur-deficient

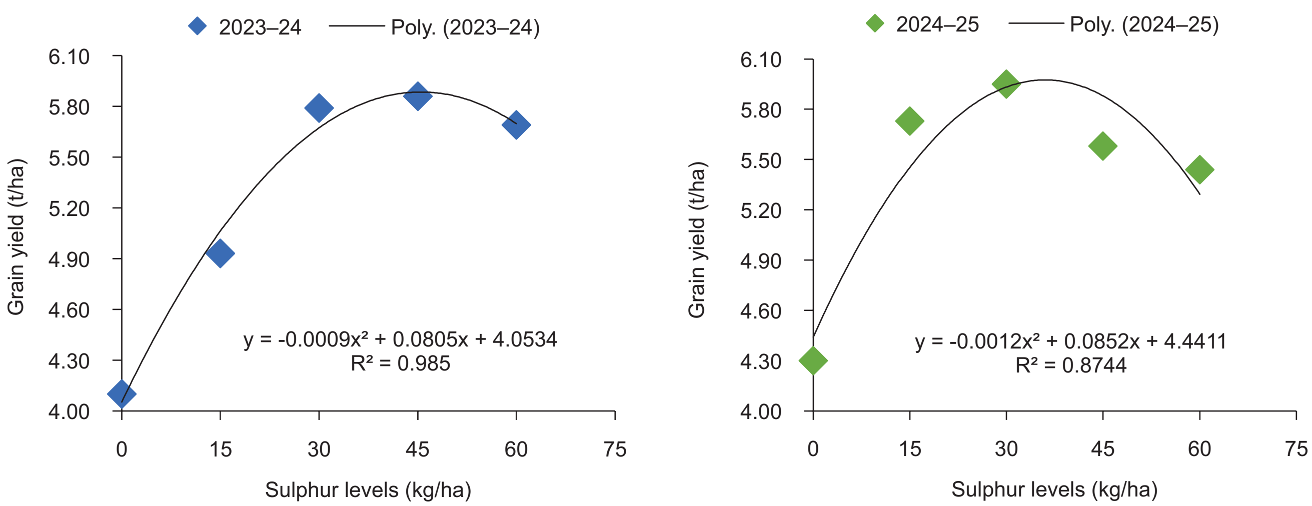

Fig. 3 Relationship between sulphur level (X) and grain yield (Y) of spring wheat (2023–24 and 2024–25).

Table 4 Pearson correlation coefficients among growth attributes, yield and efficiency of wheat

Year	Notations	PHH	TH	DWH	LAIF	SPADF	NDVIF	GY	HI	AE	PE	ME
2023–24	PHH	1										
	TH	0.91**	1									
	DMAH	0.91**	0.98***	1								
	LAIF	0.93**	0.96***	0.98***	1							
	SPADF	0.88**	0.94**	0.98***	0.99***	1						
	NDVIF	0.86**	0.93**	0.95***	0.89**	0.88**	1					
	GY	0.99***	0.96***	0.95***	0.95***	0.91**	0.91**	1				
	HI	0.92**	0.78*	0.78*	0.78*	0.76*	0.75*	0.90**	1			
	AE	0.57^{NS}	0.50^{NS}	0.53^{NS}	0.44^{NS}	0.40^{NS}	0.75*	0.59^{NS}	0.68^{NS}	1		
	PE	0.97***	0.97***	0.97***	0.96***	0.93**	0.95***	0.99***	0.87**	0.62^{NS}	1	
	ME	0.96***	0.97***	0.98***	0.97***	0.94	0.95***	0.99***	0.85	0.61	0.99***	1
	Notations	PHH	TH	DWH	LAIF	SPADF	NDVIF	GY	HI	AE	PE	ME
2024–25	PHH	1										
	TH	0.91**	1									
	DMAH	0.91**	0.98***	1								
	LAIF	0.93**	0.96***	0.98***	1							
	SPADF	0.88**	0.94**	0.98***	0.99***	1						
	NDVIF	0.86*	0.93**	0.95***	0.89**	0.88**	1					
	GY	0.99***	0.96***	0.95**	0.95***	0.91**	0.91**	1				
	HI	0.92**	0.78*	0.75*	0.76*	0.66^{NS}	0.75*	0.90**	1			
	AE	0.57^{NS}	0.50^{NS}	0.53^{NS}	0.44^{NS}	0.40^{NS}	0.76*	0.59^{NS}	0.68^{NS}	1		
	PE	0.97***	0.97***	0.97***	0.96***	0.93**	0.95***	0.99***	0.87**	0.62^{NS}	1	
	ME	0.96***	0.97***	0.98***	0.97***	0.94**	0.95***	0.99***	0.85*	0.61^{NS}	0.99***	1

PHH, Plant height at harvest; TH, Tillers at harvest; DWH, Dry weight at harvest; LAIF, Leaf area index at flowering; SPDAF, Soil plant analysis development at flowering, NDVIF, Normalised difference vegetation index at flowering; GY, Grain yield; HI, Harvest index, AE, Agronomic efficiency; PE, Production efficiency, ME, Monetary efficiency. ***, $p<0.001$; **, $p<0.01$; *, $p<0.5$. NS, Non-significant.

conditions, with 30 kg/ha as the ideal rate for maximising both profitability and sustainability in wheat-rice cropping sequence. These findings emphasise the need to integrate sulphur into balanced fertilisation strategies for sustainable wheat production systems.

From a forward-looking perspective, the results highlight the need to incorporate sulphur into integrated nutrient management programmes and region-specific fertiliser recommendations, particularly in sulphur-deficient areas (Indo-gangetic plains and rice-wheat cropping systems). Policymakers and extension agencies should promote soil testing-based sulphur application and encourage inclusion of sulphur-containing fertilisers in subsidy frameworks to ensure long-term soil fertility, higher nutrient-use efficiency and resilient wheat-rice production systems under changing climatic conditions.

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