



Effect of sulphur and micronutrient embedded fertilization on growth dynamics of wheat under diverse agroecologies

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Summary

Supplementation of micronutrients is recognized as essential for improving crop growth in intensive cereal-based cropping systems. A two-location study was conducted during 2023 and 2024 at New Delhi and Karnal to evaluate the effects of sulphur (S) and embedded fertilizers on growth dynamics of wheat. Nine treatments were replicated thrice in randomized block design, with combinations of recommended dose of fertilizers (RDF), S, zinc-embedded S (Zn-ES), multimicronutrient embedded S (MM-ES), farmyard manure (FYM), and microbial consortia. A combination of RDF + S (15 kg ha⁻¹) + Zn-ES (10 kg ha⁻¹) + MM-ES (15 kg ha⁻¹) recorded the highest leaf area index, crop growth rate (CGR), relative growth rate (RGR), and net assimilation rate (NAR). At harvest, dry matter accumulation improved by 14.3% at Karnal and CGR (45-90 DAS) reached 14.1 g m⁻² day⁻¹. Integrated sulphur and micronutrient embedded fertilization improves growth dynamics, offering a sustainable nutrient management strategy for wheat.

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Introduction

Wheat (*Triticum aestivum* L.) is the most widely cultivated cereals globally, with more than 66% used as food, meeting 20% of protein intake (FAOstat 2023). India ranks second in production (110.52 million tonnes) globally (FAOstat 2023) with wheat accounting for more than half of India's protein requirements on average (Majumdar et al. 2013). With the rising pressures from exploding population coupled with climate change, it is further challenging to meet the demand for wheat in quantity and quality (Farhad et al., 2023). Intensive cereal-based cropping system, such as rice-wheat cropping system predominant in the Indo-Gangetic Plain (IGP) regions has already resulting in multitude of issues with deficiency of both macros as well micronutrients becoming more prominent (Nawaz et al. 2019) in soils cultivated for wheat. Neglecting secondary nutrients such as sulphur (S) and essential micronutrients including zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) further making this more widespread (Scherer, 2009; Zhang et al., 2015). Zinc deficiency has been reported in nearly 50% cultivated soils of India, severely limiting crop growth and nutrient-use efficiency (Alloway, 2009). Sulphur is crucial in plant metabolism as an integral component of sulphur-containing amino acids and is directly involved in protein synthesis, chlorophyll formation, and enzymatic activation along with improving nitrogen use efficiency (Scherer 2001; Salvagiotti et al. 2009). Zinc

and other micronutrients regulate key physiological and biochemical processes, including enzyme activation, hormone synthesis, membrane stability, and photosynthetic efficiency (Broadley et al. 2012). Deficiencies of sulphur and micronutrients resulted reduced leaf area development, poor canopy architecture, lower dry matter accumulation, and impaired assimilatory capacity, ultimately resulting in sub-optimal crop growth (Cakmak 2008). These limitations may not always produce distinct visual symptoms but significantly constrain physiological efficiency and yield potential (Alloway 2009). Moreover, nutrient interactions are highly complex, and imbalanced fertilization with macronutrients alone can exacerbate secondary and micronutrient deficiencies, reducing the effectiveness of applied NPK fertilizers (Kumar et al. 2021). Growth parameters such as dry matter accumulation and leaf area index (LAI), along with growth indices including crop growth rate (CGR), relative growth rate (RGR), and net assimilation rate (NAR), provide mechanistic insights into crop growth dynamics and physiological performance (Radford, 1967). These indices reflect the crop's ability to intercept radiation, assimilate carbon, and convert assimilates into biomass across different growth stages (Hunt 1990). Evaluating growth indices can provide a deeper insight of influence of nutrient management strategies on crop growth processes beyond final yield outcomes (Monteith & Moss 1977).

Recent advancements in fertilizer technology have led to the development of micronutrient embedded sulphur formulations, such as zinc-embedded sulphur (Zn-ES) and multimicronutrient embedded sulphur (MM-ES), designed to supply sulphur and micronutrients synchronously with crop

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demand (Prasad 2013). Such formulations are particularly beneficial under semi-arid environments, where soil moisture variability and nutrient losses often constrain crop growth (Lal 2015). Despite increasing recognition of the importance of sulphur and micronutrient nutrition, systematic field-based evaluations of micronutrient-embedded sulphur fertilizers on wheat growth dynamics remain limited, particularly under diverse environment. Most previous studies have focused primarily on grain yield responses, with limited emphasis on growth parameters and physiological indices that plays a crucial role in yield formation (Kumar et al. 2019). Furthermore, comparative evaluations of full and reduced NPK fertilization integrated with sulphur, micronutrients, organic manures, or microbial consortia across multiple environments remain scarce. Therefore, the present study was undertaken to evaluate the effects of integrated sulphur and micronutrient embedded fertilization on growth parameters and growth indices of wheat under two representative semi-arid locations of northern India. The specific objectives were to (i) assess the influence of integrated sulphur and micronutrient management on dry matter accumulation and leaf area development, (ii) quantify the response of CGR, RGR, and NAR at different growth stages, and (iii) identify efficient nutrient management strategies capable of sustaining vigorous wheat growth under intensive cereal-based production systems.

Materials and methods

Study locations and design of experiment

An experiment was conducted in the 2023 and 2024 cropping seasons at northern semi-arid climates of Indian Agricultural Research Institute, New Delhi (28° 4' N, 77° 12' E, 228.6 m altitude), Indian Agricultural Research Institute Regional Station, Karnal (29° 7' N, 76° 99' E, 237.6 m altitude). The average maximum and minimum temperature for New Delhi were 35.5°C and 24.8°C, respectively in 2023 and 35.6°C and 26°C, respectively in 2024. In Karnal, the average maximum temperature ranged from 32.3-38.4°C and 31.8-43.8°C in 2023 and 2024, respectively. The total precipitation for the cropping season was 579.1 and 732.9 mm in the year 2023 and 2024, respectively in New Delhi. The New Delhi site had the least rainfall. Composite soil samples were taken from furrow slice (0-150 mm depth) before sowing for each site and analysed for soil physical and chemical properties. The soil texture was identified as sandy loam in New Delhi, whereas the clay loam soil was observed in Karnal. The experimental soils of New Delhi and Karnal had low soil organic carbon (SOC) with a value of 0.45 and 0.48%, respectively. The plant-available nitrogen was lower, with 162.5 kg ha⁻¹ at New Delhi, and 112.4 kg ha⁻¹ at Karnal, respectively. Soils of New Delhi and Karnal recorded moderate levels of plant-available P with value reaching at 16.9 kg ha⁻¹ and 20.1 kg ha⁻¹, respectively. Similarly, moderate level of K with 261.2 kg ha⁻¹ and 202.2 kg ha⁻¹ were also observed in New Delhi and Karnal, respectively. In addition, soils of New Delhi and Karnal were slightly alkaline in reaction with pH value of 7.8 and 7.9.

Treatment details

The experiment had nine treatments in a Randomized Complete Block Design (RCBD) with three replications with net plot size of 20 m². Fertilizers -N, -P and -K were applied at the recommended Doses of Fertilizer (RDF) for treatment T1 of 120, 60 and 60 kg ha⁻¹ (Table 1) which were supplied through urea, Single Super Phosphate (SSP), Muriate of Potash (MOP). Nine treatments consisted of varied combinations of 100, 75 or 50% of Recommended Doses of Fertilizer (RDF) along with Sulphur (90% S), Zn- embedded S (Zn-ES), and micronutrient embedded S (MM-ES), which were compared against control, microbial consortia and farmyard manure (FYM) application (Table 1). One-third dose of nitrogen was applied as basal and 2/3rd as split dose in two equal splits. The Zn-ES and MM-ES were applied twice, at pre-planting and at 30 days after sowing (DAS) in T4, while only single basal dose was applied in case of other treatments.

Table 1. Treatment details

Treatment no.	Treatment Details
T ₁	Normal Fertilizer application as per RDF (Recommended Dose of Fertilizer)
T ₂	75% RDF + S 15 kg ha ⁻¹ + Zn-ES (Zn-embedded S) 10 kg ha ⁻¹ + MM-ES (Multi-micronutrient embedded S) 15 kg ha ⁻¹ (applied as basal)
T ₃	75% RDF + Zn-ES 20 kg ha ⁻¹ + MM-ES 20 kg ha ⁻¹ (basal)
T ₄	50% RDF + Zn-ES 20 kg ha ⁻¹ + MM-ES 20 kg ha ⁻¹ (basal) + Zn-ES 20 kg ha ⁻¹ and MM-ES 20 kg ha ⁻¹ (top dressing at 15-30 DAS)
T ₅	100% RDF + Zn-ES 20 kg ha ⁻¹ + MM-ES 20 kg ha ⁻¹ (basal)
T ₆	100% RDF + S 15 kg ha ⁻¹ + Zn-ES 10 kg ha ⁻¹ + MM-ES 15 kg ha ⁻¹ (basal)
T ₇	No fertilizer control
T ₈	75% RDF+5 t ha ⁻¹ FYM
T ₉	75% RDF+ microbial consortia (<i>Pusa Sampoorna</i>)

Crop management

The wheat variety 'HD 2967' was sown in first fortnight of November using 100 kg seeds ha⁻¹ during both experimental years (2023-24 & 2024-25). Need-based irrigations each with 60 mm depth using a water meter were applied. For weed control in wheat, sulfosulfuron @ 30 g ha⁻¹ and metsulfuron-methyl @ 4 g ha⁻¹ for controlling broad-leaved as well as narrow-leaved weeds. Other crop protection practices such as pest and disease management were followed when needed.

Growth parameters of wheat

For calculating dry matter accumulation, second row from one side of the plot was selected from each plot. Five plants of wheat and wheat were cut to the ground and then dried in the oven at 60-65°C to get constant weight at 45 DAS, 90 DAS and at harvest. The dry weight obtained was divided by 5 to get dry matter accumulation per plant and then converted into g m⁻² using crop spacing. Using leaf area meter, leaf area per plant was calculated and divided by the respective

ground area to get leaf area index at 45DAS, 90DAS, and at harvest. Formula used for calculating LAI is given below:

$$\text{LAI} = \frac{\text{Total leaf area plant}^{-1}(\text{cm}^2)}{\text{Land area plant}^{-1}(\text{cm}^2)}$$

Growth indices of wheat

Crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR) were computed between 0-45 DAS, 45-90 DAS and 90 DAS-harvest using the formulae (Radford 1967).

$$\text{CGR (g m}^{-2} \text{ day}^{-1}) = \frac{(W_2 - W_1)}{(t_2 - t_1)} \times \frac{1}{P}$$

$$\text{RGR (g g}^{-1} \text{ day}^{-1}) = \frac{\ln W_2 - \ln W_1}{(t_2 - t_1)}$$

$$\text{NAR (g m}^{-2} \text{ day}^{-1}) = \frac{(W_2 - W_1)}{(t_2 - t_1)} \times \frac{\ln L_2 - \ln L_1}{L_2 - L_1}$$

$$\frac{\ln L_2 - \ln L_1}{L_2 - L_1}$$

Where, W1, W2= total dry matter accumulation (g) at time t1 and t2, respectively, L1, L2 = Leaf area (m²) at time t1 and t2, respectively, P= ground area (m²)

Results

Growth parameters of wheat

Table 2. Effect of sulphur and micronutrient management on dry matter accumulation in wheat

Treatments	Dry Matter Accumulation (g m ⁻²)											
	At 45 DAS				At 90 DAS				At harvest			
	Delhi		Karnal		Delhi		Karnal		Delhi		Karnal	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
T1	149.9	147.9	148.6	151.7	712.0	717.7	720.4	730.2	1112.4	974.0	1109.0	1111.8
T2	151.2	153.1	151.2	154.0	733.7	747.3	742.8	758.3	1159.7	1042.2	1145.6	1156.1
T3	150.5	152.6	150.4	152.4	719.3	737.2	730.7	744.2	1129.6	1026.1	1126.1	1134.5
T4	123.0	130.5	124.0	125.7	552.0	568.6	565.6	575.2	810.5	708.4	824.3	827.2
T5	152.1	155.0	154.2	155.9	719.8	763.1	755.4	768.9	1172.0	1065.5	1171.3	1173.4
T6	152.5	158.0	158.0	160.4	752.4	776.6	778.7	799.0	1230.3	1089.2	1219.7	1220.5
T7	102.1	125.0	108.9	105.5	476.0	535.3	484.0	482.2	688.7	620.3	697.2	654.5
T8	148.6	147.0	146.9	149.4	696.3	644.1	699.2	706.5	1046.8	813.8	1039.1	1020.5
T9	144.9	142.4	142.7	145.8	651.7	623.0	674.6	684.2	967.5	780.7	986.9	987.0
SEm±	1.35	3.85	1.65	3.52	8.57	15.14	5.22	15.85	15.86	24.08	7.71	17.13
CD (P=0.05)	4.06	11.56	4.94	10.55	25.71	45.39	15.66	47.52	47.57	72.21	23.14	51.36

(T1: RDF; T2: 75% RDF+S 15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T3: 75% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T4: 50% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹ (basal and 30DAS); T5: RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T6: 75% RDF + S-15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T7: Control; T8: 75% RDF + 5 t ha⁻¹ FYM; T9: 75% RDF + Microbial consortia)

Leaf area index

Leaf Area Index (LAI) increased from 45 DAS to 90 DAS and declined sharply by harvest across all treatments and both locations (Figure 1). At 45 DAS, LAI ranged from 1.00-2.62 in Delhi and 1.02-2.66 in Karnal, with T6 consistently recording the highest leaf area index (2.58-2.66) and T7 the lowest (1.00-1.62). By 90 DAS, LAI reached its maximum, varying between 1.01-3.17 in Delhi and 1.08-3.12 in Karnal, again with T6 outperforming all treatments. At harvest, LAI declined

Dry matter accumulation

Dry matter accumulation (DMA) in wheat increased progressively from 45 DAS to harvest with maximum value reached at harvest across both locations and years (Table 2). At 45 DAS, DMA ranged from 102.1-158.0 g m⁻² in Delhi and 105.5-160.4 g m⁻² in Karnal, with T6 consistently exhibiting the highest biomass and T7 the lowest. By 90 DAS, biomass accumulation increased sharply, ranging from 476.0-776.6 g m⁻² in Delhi and 482.2-799.0 g m⁻² in Karnal, with T6 showing a clear advantage over all other treatments. At harvest, maximum DMA was achieved in T6 (1089.2-1230.3 g m⁻² in Delhi; 1219.7-1220.5 g m⁻² in Karnal), followed by T5 (RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹) and T2 (75% RDF + S 15 kg ha⁻¹ + Zn-ES 20 kg ha⁻¹ + MM-ES 15 kg ha⁻¹), whereas T7 recorded the lowest biomass reaching as low as 620.3 g m⁻². Comparison between locations showed that Karnal recorded higher dry matter accumulation than Delhi by approximately 14.3% at harvest.

substantially due to senescence, with values ranging from 0.31-1.34 in Delhi and 0.44-1.33 in Karnal, while T6 again exceeded rest of the treatments (1.12-1.33). The LAI was improved in T6 by 14.1-21.8% at 45 DAS, 9.4-37.2% at 90 DAS and 20.3-33.0% at harvest. Across stages, Karnal exhibited overall higher LAI than Delhi, with increases of 4.1-6.1% at 45 DAS, 3.8-7.9% at 90 DAS, and 4.0-8.3% at harvest, reflecting comparatively favourable environmental conditions for leaf development.

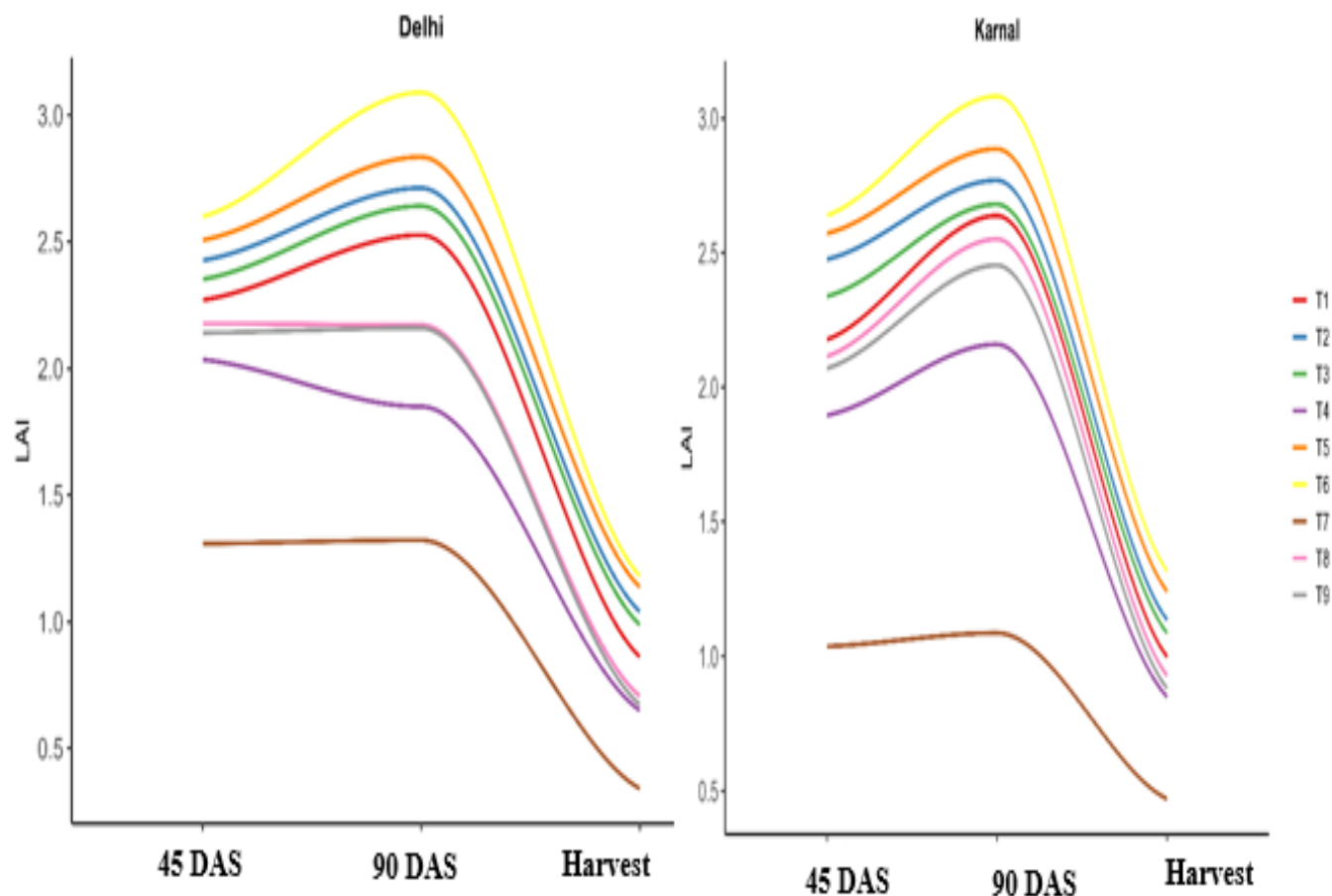


Figure 1. Leaf Area Index of wheat across treatments in both locations

(T1: RDF; T2: 75% RDF + S 15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T3: 75% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T4: 50% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹ (basal and 30 DAS); T5: RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T6: 75% RDF + S-15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T7: Control; T8: 75% RDF + 5 t ha⁻¹ FYM; T9: 75% RDF + Microbial consortia)

Growth indices of wheat

Crop Growth Rate

The crop growth rate (CGR) of wheat followed a sigmoidal pattern with a gradual increase from 0-45 DAS (2.2-3.6 g cm⁻² day⁻¹), with reaching maximum CGR at 90 DAS (8.3-14.2 g cm⁻² day⁻¹), and decline at harvest, at both the locations. Treatments integrating RDF with sulphur, Zn-ES, MM-ES, FYM, or microbial consortia (notably T6, T5, and T8) exhibited the highest peak of CGR at all the growth stages, suggesting statistically superior growth performance and prolonged source strength. However, application of RDF along with S 15 kg ha⁻¹, Zn-ES 10 kg ha⁻¹ and MM-ES 15 kg ha⁻¹ (T6) recorded highest CGR at all the growth stages with peak observed during 45-90 DAS (13.3-13.7 g m⁻² day⁻¹ in Delhi; 13.8-14.1 g m⁻² day⁻¹ in Karnal). T5 was the next best treatments with higher CGR at all the growth stages across locations and years. T8 (75% RDF + FYM 5 t ha⁻¹) and T9 (75% RDF + Microbial consortia) achieved comparable CGR and superior to control at both locations confirming beneficial role of organic matter supplementation with reduced dose of

fertilizers. T7 (control) resulted in lowest CGR at all the growth stages across locations and years. Across locations, Karnal recorded relatively higher CGR compared to Delhi.

Relative Growth Rate and Net Assimilation Rate

The trends of Relative Growth Rate (RGR) and Net Assimilation Rate (NAR) of wheat exhibited a declining pattern across crop growth stages (0-45 DAS, 45-90 DAS, and 90 DAS-harvest) at both locations, though there was no significant difference across treatments. The RGR was highest during the early growth stage (0-45 DAS), followed by a sharp reduction during 45-90 DAS, and further reduced towards harvest. Likewise similar trend across treatments was observed with the highest value was observed in T6 for both RGR (111.7-112.4 mg g⁻¹ day⁻¹ in Delhi, 112.5-112.8 mg g⁻¹ day⁻¹ in Karnal during 0-45 DAS), whereas NAR (1.3-2.2 mg cm⁻² day⁻¹) was highest in control (T7). Again, T8 and T9 remained statistically identical in increasing RGR and NAR. In contrast, reduced fertilizer application (T3 and T4) resulted in identical RGR and NAR during 45-90 DAS, suggesting statistically comparable.

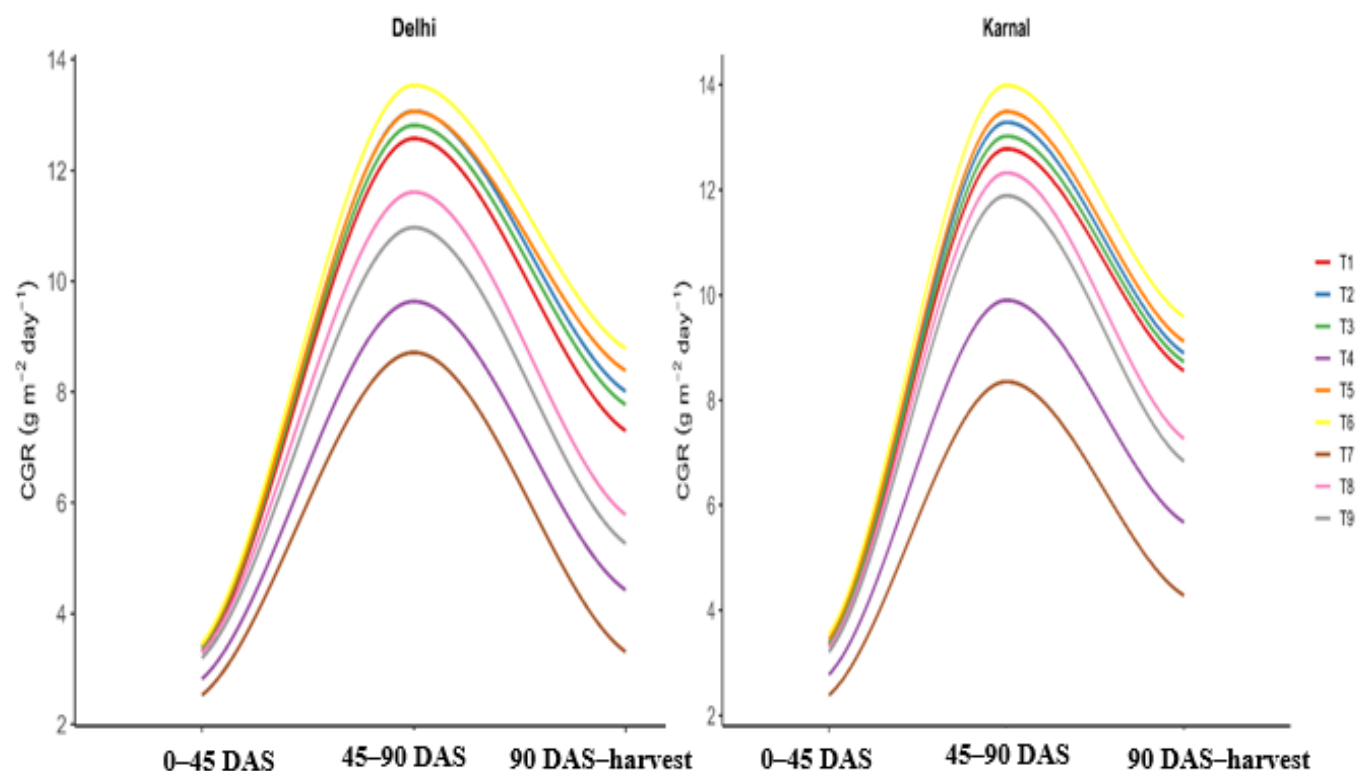


Figure 2. Crop Growth rate (CGR) of wheat across treatments in both locations

(T1: RDF; T2: 75% RDF+S 15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T3: 75% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T4: 50% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹ (basal and 30DAS); T5: RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T6: 75% RDF + S-15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T7: Control; T8: 75% RDF + 5 t ha⁻¹ FYM; T9: 75% RDF + Microbial consortia)

Table 3. Effect of sulphur and micronutrient management on Relative Growth Rate (RGR) of wheat

Treatments	Relative Growth Rate (mg g ⁻¹ day ⁻¹)											
	0-45 DAS				45-90 DAS				90DAS-harvest			
	Delhi		Karnal		Delhi		Karnal		Delhi		Karnal	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
T1	111.3	111.0	111.1	111.6	34.63	35.10	35.08	34.92	9.92	6.78	9.58	9.35
T2	111.5	111.8	111.5	111.9	35.10	35.23	35.37	35.42	10.18	7.37	9.63	9.38
T3	111.4	111.7	111.4	111.7	34.76	34.99	35.13	35.25	10.03	7.33	9.61	9.37
T4	106.9	108.2	107.1	107.4	33.37	32.71	33.74	33.79	8.53	4.89	8.37	8.11
T5	111.7	112.1	112.0	112.2	34.53	35.42	35.32	35.46	10.85	7.42	9.75	9.40
T6	111.7	112.5	112.5	112.8	35.48	35.39	35.44	35.70	10.93	7.51	9.98	9.42
T7	102.8	107.3	104.2	103.5	34.20	32.35	33.14	33.75	8.21	3.23	8.11	6.79
T8	111.1	110.9	110.9	111.3	34.33	32.83	34.67	34.51	9.03	5.19	8.80	8.17
T9	110.6	110.2	110.2	110.7	33.40	32.80	34.52	34.33	8.76	5.00	8.45	8.16
SEm±	0.20	1.43	0.27	0.53	0.35	0.95	0.32	0.67	0.44	0.79	0.23	0.43
CD (P=0.05)	0.84	2.53	1.15	2.21	1.46	NS	1.32	NS	1.83	3.26	0.96	1.78

(T1: RDF; T2: 75% RDF+S 15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T3: 75% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T4: 50% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹ (basal and 30DAS); T5: RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T6: 75% RDF + S-15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T7: Control; T8: 75% RDF + 5 t ha⁻¹ FYM; T9: 75% RDF + Microbial consortia)

Table 4. Effect of sulphur and micronutrient management on Net Assimilation Rate (NAR) of wheat

Treatments	Net Assimilation Rate (mg cm ⁻² day ⁻¹)											
	0-45 DAS				45-90 DAS				90DAS-harvest			
	Delhi		Karnal		Delhi		Karnal		Delhi		Karnal	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
T1	1.49	1.47	1.55	1.55	0.51	0.56	0.54	0.54	0.51	0.43	0.52	0.51

T2	1.42	1.42	1.40	1.41	0.50	0.54	0.50	0.53	0.50	0.42	0.49	0.50
T3	1.45	1.46	1.48	1.44	0.49	0.56	0.52	0.53	0.49	0.44	0.50	0.50
T4	1.41	1.37	1.51	1.42	0.48	0.52	0.51	0.49	0.42	0.35	0.41	0.41
T5	1.40	1.40	1.36	1.39	0.48	0.52	0.49	0.51	0.52	0.38	0.47	0.48
T6	1.35	1.39	1.38	1.38	0.48	0.48	0.49	0.50	0.54	0.36	0.48	0.46
T7	2.12	1.69	2.15	2.17	0.84	0.57	0.79	0.81	0.81	0.22	0.67	0.53
T8	1.58	1.50	1.55	1.59	0.54	0.55	0.54	0.54	0.50	0.40	0.47	0.45
T9	1.59	1.43	1.55	1.57	0.51	0.53	0.54	0.54	0.46	0.36	0.46	0.45
SEm±	0.02	0.09	0.03	0.07	0.01	0.02	0.01	0.03	0.03	0.05	0.01	0.03
CD (P=0.05)	0.08	NS	0.12	0.32	0.06	NS	0.04	0.13	0.14	NS	0.06	NS

(T1: RDF; T2: 75% RDF + S 15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T3: 75% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T4: 50% RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹ (basal and 30DAS); T5: RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹; T6: 75% RDF + S-15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹; T7: Control; T8: 75% RDF + 5 t ha⁻¹ FYM; T9: 75% RDF + Microbial consortia)

Discussion

Significant variations in growth parameters of wheat were noted with application of different combination of sulphur and micronutrients. Maximum leaf area index, and dry matter accumulation were recorded with application of RDF + S 15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹ (T6) followed by T5 (RDF + Zn-ES 20 kg ha⁻¹ + MM-ES 20 kg ha⁻¹) and T2 (75% RDF + S 15 kg ha⁻¹ + Zn-ES 10 kg ha⁻¹ + MM-ES 15 kg ha⁻¹). Lowest values of growth attributes were observed in the control (T7). Significantly higher leaf area index under T6 across all growth stages indicates stimulation of cell division, elongation leading to overall vigor as a result of synergistic interaction of NPK with S, Zn and other micronutrients (Magodia et al. 2024; Jena et al. 2025). The relatively lower growth recorded under nutrient-deficient treatments such as T4 (50% RDF along with twice application of Zn-ES and MM-ES each at 20 kg ha⁻¹) and T7 (control) further confirms the critical role of balanced nutrient supply (Suganya et al., 2020; Capo et al., 2024). Reduced growth attributes under nutrient stress was also reported by Joshi et al. (2016), where insufficient N and S restricted vegetative expansion.

The maximum dry matter accumulation at all the growth stages in both the locations might have been attributed to the enhanced photosynthetic efficiency due to enzyme activation, greater nutrient uptake, delayed leaf aging leading to better translocation of carbohydrate for prolonged period (Chibane et al. 2021). Similarly, a higher LAI under these treatments indicates enhanced canopy development which is crucial for radiation interception and carbon assimilation (Adarsha et al. 2019; Jena et al. 2025). Further, increased LAI at 90 DAS with the application of RDF in combination with S and micronutrients might be owing to the delayed leaf aging and better physiological activity in wheat and wheat (Nadim et al. 2012; Adarsha et al. 2019). Decline in LAI at harvest is typical pattern in both the crops due to senescence at later stages of growth.

The CGR showed a typical sigmoidal growth pattern, with peak values observed from 45-90 DAS with T6 demonstrating the highest CGR and RGR which might be owing to the delayed leaf aging, increased physiological activities in presence of micronutrients (Kumar et al. 2019; Tsopoe et al. 2021). Further, net

assimilation rate across the locations was higher due to enhanced photosynthetic activity and nutrient uptake efficiency with the application of S, and micronutrients. The comparable CGR values in T5 and T8 (RDF + FYM) highlight the complementary role of organic manure, which improves soil physical properties, microbial activity and nutrient release, thereby sustaining CGR (Kadam et al. 2022). The lowest CGR in control (T7) and highest decline after 90 DAS might be as a result of reduced assimilatory surface. The highest NAR was achieved with T6 might be attributed to higher photosynthetic efficiency due to enhancement of carbonic anhydrase as a result of Zn. Increase in other growth attributes might be due to continued and balanced supply of nutrients right from early stage of growth resulted in vigorous plant growth (Hussain & Leitch 2008).

Conclusion

The results clearly demonstrate that integrated application of sulphur and micronutrient embedded fertilizers significantly enhances wheat growth performance under semi-arid conditions. The combined application of RDF with sulphur, zinc-embedded sulphur, and multimicronutrient embedded sulphur consistently produced the highest dry matter accumulation, leaf area index, and growth indices across locations and years. Treatments integrating reduced RDF with micronutrients or FYM also showed comparable growth responses, indicating scope for integration. Combination of sulphur and micronutrient nutrition emerges as a sustainable strategy for improving wheat growth dynamics in intensive cereal based cropping systems of semi-arid regions.

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Author contributions

TJ: Conceptualization, Investigation, Methodology, Formal Analysis, Validation, Visualization, Writing - original draft; RSB: Conceptualization, Funding acquisition, Project administration, Supervision, Investigation, Methodology, Validation, Writing - original draft, Writing - review and editing; TS: Data curation, Formal analysis, Visualization, Writing-review and editing; CMP: Validation, Supervision, Writing -

review and editing; AY: Supervision, Writing - review and editing; PGD: Data curation, Formal analysis, Visualization

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