



RESEARCH ARTICLE

Effect of sole and combined application of sulphatic micronutrients fertilisers on growth traits of wheat (*Triticum aestivum* L.)

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Abstract

Hidden hunger due to inadequate availability of micronutrients such as Zn, Fe and Cu often limits wheat productivity despite sufficient macronutrient supply. A field experiment was conducted during the rabi seasons of 2022–23 and 2023–24 at Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, to evaluate the effect of sulphate-based micronutrient fertilisation on the growth performance of wheat varieties. The study was laid out in a split-plot design with 2 varieties as main plots and 10 nutrient management treatments, including control, as subplots. Results revealed that variety DBW-222 exhibited superior growth performance over HD-2967 in terms of plant height, tiller density, dry matter production, crop growth rate and grain yield. Among nutrient management practices, the treatment, recommended dose of fertilisers (RDF) + soil application of (Zn + Fe + Cu) through ZnSO₄·7H₂O at 20 kg ha⁻¹, FeSO₄·7H₂O at 12 kg ha⁻¹, CuSO₄·5H₂O at 2.0 kg ha⁻¹ significantly enhanced plant height, tiller number, dry matter accumulation (DMA), crop growth rate (CGR) and grain yield compared to control and individual applications. This treatment also reduced days to heading and maturity, indicating improved crop vigour and growth efficiency. The period of 60–90 days after sowing (DAS) was identified as the most critical stage for rapid biomass accumulation. Overall, the study demonstrates that combined soil application of Zn, Fe and Cu substantially improves wheat growth and can be recommended as an effective strategy to address micronutrient deficiencies and enhance crop performance.

Keywords: agriculture; biomass; fertilisation; hidden hunger; vigour

Introduction

Wheat (*Triticum aestivum* L.) is one of the major foodgrain crops, which provides nearly 20 % calories and protein per capita throughout the world (1). Since, wheat being the staple cereal crop of India, the concentration of micronutrients (Fe, Zn and Cu) in grains plays a vital role in human health (2–5). About 2 billion people suffers from hidden hunger across the globe in which approximately 815 million people suffer due to micronutrient deficiency as per the World Health Organization (6). In the past few years, cereal crops, especially wheat, have gained considerable attention in view of their potential role in the transport of microelements into the human diet (7, 8). In wheat grains, the bioavailability of Zn and Fe is about 25 % and 5 % respectively (9). The bioavailability of Zinc and iron is associated with the presence of antinutrients, such as phytate and a lack of promoter substances in grains (10). The uptake and remobilisation of zinc and iron is facilitated by some nutrients. For example, the combination of nitrogen fertiliser with Zn and Fe applied in soil or on leaves (foliar) increases both the yield and the uptake of these

elements (11). Sulphur is another element which is involved in assisting Zinc and Iron metabolism in plants (12). The ability of the plant to absorb and accumulate Fe proved to be dependent on the presence of S in growing medium in cereals crops (13). Sulphate based micronutrient fertilisers viz. ZnSO₄, FeSO₄, CuSO₄ are found to be most suitable for cereals crops as they contain sulphur element, which have the beneficial effect

In India, soils are deficient in micronutrients elements, especially Zn (14, 15), so the application of micronutrient fertilisers becomes crucial for the plant growth and development. As Zn is important for human beings, it is equally crucial for plant growth, where it is required in small quantity, but its deficiency leads to reduced yield and poor grain quality (16, 17). The inadequate supply of Zn and other micronutrients like Fe and Cu affects the metabolism of plant, stunted growth and delayed maturity (18). Various studies have revealed that fertilising with Zn (19) and other micronutrients can increase grain yield, as well as enhance plant height, grain weight and number of tillers (20). This study aimed to evaluate the effect of sulphate-based micronutrient fertilisers on growth attributes of wheat.

Materials and Methods

Experimental site

The experiment was conducted in the Student's Instructional Farm (SIF) of the Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, India situated at a latitude of 26.493729° N and longitude of 80.294382° E and an altitude of 125.9 m above the mean sea level (MSL) during the rabi seasons of 2022–23 and 2023–24. The climate of the site is sub-tropical having maximum and minimum temperature ranges from 45–4 °C. The soil was sandy loam in texture with pH of 7.7 and available N (186.5 kg ha⁻¹), P (17.5 kg ha⁻¹) and K (319.9 kg ha⁻¹).

Treatment details

The experiment was laid out in a Split Plot Design (SPD) with 3 replications. The main plot consisted of 2 widely cultivated wheat varieties, namely DBW-222 (V₁) and HD-2967 (V₂). The sub-plot treatments included nutrient management strategies which are – control-RDF (T₀); RDF (recommended dose of fertilisers) + soil application of Zn through ZnSO₄.7H₂O @ 20 Kgha⁻¹(T₁); RDF + foliar spray of Zn as 1.0 % ZnSO₄.7H₂O at tillering and booting stages (T₂); RDF + soil application of Fe through FeSO₄.7H₂O at 12 Kg ha⁻¹(T₃); RDF + foliar spray of Fe as 1.5 % FeSO₄.7H₂O at tillering and booting stages (T₄); RDF + soil application of Cu through CuSO₄.5H₂O at 2.0 Kg ha⁻¹(T₅); RDF + foliar spray of Cu as 0.1 % CuSO₄.7H₂O at tillering and booting stages (T₆); RDF + foliar spray of (Zn + Fe) as 1.0 % ZnSO₄.7H₂O and 1.5 % FeSO₄.7H₂O at tillering and booting stages (T₇); RDF + soil application of (Zn + Fe+ Cu) through ZnSO₄.7H₂O at 20 Kg ha⁻¹, FeSO₄.7H₂O at 12 Kg ha⁻¹, CuSO₄.5H₂O at 2.0 Kg ha⁻¹(T₈); RDF + foliar application of (Zn + Fe + Cu) as 1.0 % ZnSO₄.7H₂O, 1.5 % FeSO₄.7H₂O and 0.1 % CuSO₄.5H₂O at tillering and booting stages (T₉). The crop was fertilised with the RDF at the rate of 120:60:40 kg ha⁻¹ of N, P₂O₅ and K₂O respectively, applied as per standard agronomic practices. A recommended seed rate of 100 kg/ha was used. The sowing was done in lines 22.5 cm apart from each other.

Phosphorus was applied at 60 kg P₂O₅ ha⁻¹ through di-ammonium phosphate (DAP). Nitrogen (N) was applied at the recommended dose of 120 kg ha⁻¹. As DAP has supplied around 23.5 kg N ha⁻¹, so remaining dose of N was supplied through urea (46 % N) for completing recommended dose. Nitrogen was applied in 2 equal splits i.e. half at the time of sowing and the remaining as top dressing. Muriate of potash (MOP) was applied at the time of sowing at the rate of 40 kg K₂O ha⁻¹.

The soil application of zinc sulphate, iron sulphate and copper sulphate were done as per treatment before sowing, except in control. The foliar sprays of zinc sulphate, iron sulphate and copper sulphate were made as per the treatments by taking 300 L ha⁻¹ spray volume. The foliar spray of the micronutrient fertilisers was done 2 times; 1st spray at tillering stage and 2nd spray at booting stage.

Dry matter production (g m⁻²)

Five plants were randomly selected in each plot for the calculation of dry matter production by wheat crop at 45, 60, 90, 120 DAS and at harvest stage. Selected plants were carefully uprooted out from the field and sun dried for 2–3 days. Thereafter, the samples were oven dried at 65 °C for 24 hr. The dried samples were weighed in electronic balance and the final dry weight was recorded in g m⁻².

Crop growth rate (CGR)

Crop growth rate expresses the gain in dry matter production of

the crop per unit area per unit time and is expressed as g/m² per day (g m⁻² day⁻¹). The dry matter data recorded at 30 days interval up to maturity were used to calculate the CGR with the following formula (21).

$$\text{CGR} = \frac{(w_2 - w_1)}{(t_2 - t_1)} \text{ (g m}^{-2} \text{ day}^{-1}\text{)}$$

whereas,

w₁ is the initial dry mass accumulation (g)

w₂ is the dry mass accumulation at a later time (g)

t₂ – t₁ is the time difference (in days) between the 2 measurements

Statistical analysis

The data was statistically analysed using the OPSTAT web server. Statistical significance was tested at 5 % (p = 0.05) level.

Results and Discussion

Plant height (cm)

Table 1 presents the plant height data at 45 DAS where the height of wheat variety, DBW-222 (36.3 cm) was higher than HD-2967 (33 cm). At 60 DAS, wheat variety DBW-222 (58.08 cm) showed a significant advantage over HD-2967 (51.05 cm) during the 2022–23 growing season at 60 DAS. Among nutrient management treatments, the treatment T₈ (Soil application of Zn + Fe+ Cu through ZnSO₄. 7H₂O at 20 kg ha⁻¹, FeSO₄. 7H₂O at 12 kg ha⁻¹, CuSO₄.5H₂O at 2.0 Kg ha⁻¹) recorded the maximum plant height (57.34 cm), followed closely (56.07 cm) by foliar spray treatment (T₉), which involved foliar application of Zn + Fe + Cu as 1.0 % ZnSO₄.7H₂O, 1.5 % FeSO₄.7H₂O and 0.1 % CuSO₄.5H₂O at tillering and booting stages. The lowest height (52.17 cm) was noted under control (T₀). A similar pattern was observed in the subsequent year, 2023–24, with DBW-222 (57.39 cm) surpassing HD-2967 (50.36 cm). Soil-applied combined micronutrient treatment T₈ remained superior (56.65 cm), closely followed by foliar treatment T₉ (55.38 cm), whereas control plots (T₀) had the lowest plant height (51.48 cm). The pooled analysis consistently indicated superior plant height for DBW-222 (57.74 cm) over HD-2967 (50.71 cm). The treatment T₈ showed highest pooled height (57 cm), followed by T₉ (55.73 cm) and T₀(control) remained lowest (51.83 cm). Notably, the treatment (T₇) which involved foliar spray of Zn + Fe as 1.0 % ZnSO₄. 7H₂O and 1.5 % FeSO₄. 7H₂O at tillering and booting stages performed better plant height (55.01 cm) at pooled than the treatments involving individual application of micronutrient fertilisers whether applied through soil or foliar methods. These findings clearly suggest that the combined application of zinc, iron and copper; either through soil or foliar methods is more effective in promoting plant height than the individual application of these micronutrients alone. Thus, combined application of Zn, Fe and Cu enhanced plant height by improving enzymatic activity, chlorophyll synthesis and cell division.

Similar trend was also observed at 90 DAS and harvest stage with DBW-222 again surpassing HD-2967, while among the treatments, soil applied combined Zn + Fe + Cu was superior. The graph presented in Fig. 1 clearly illustrates the variation in plant height at the harvest stage among different varieties and nutrient management treatments, while the detailed numerical data are provided in Table 1. The graphical trend shows that DBW222 (V₁) attained the greatest plant height among all varieties, reaching

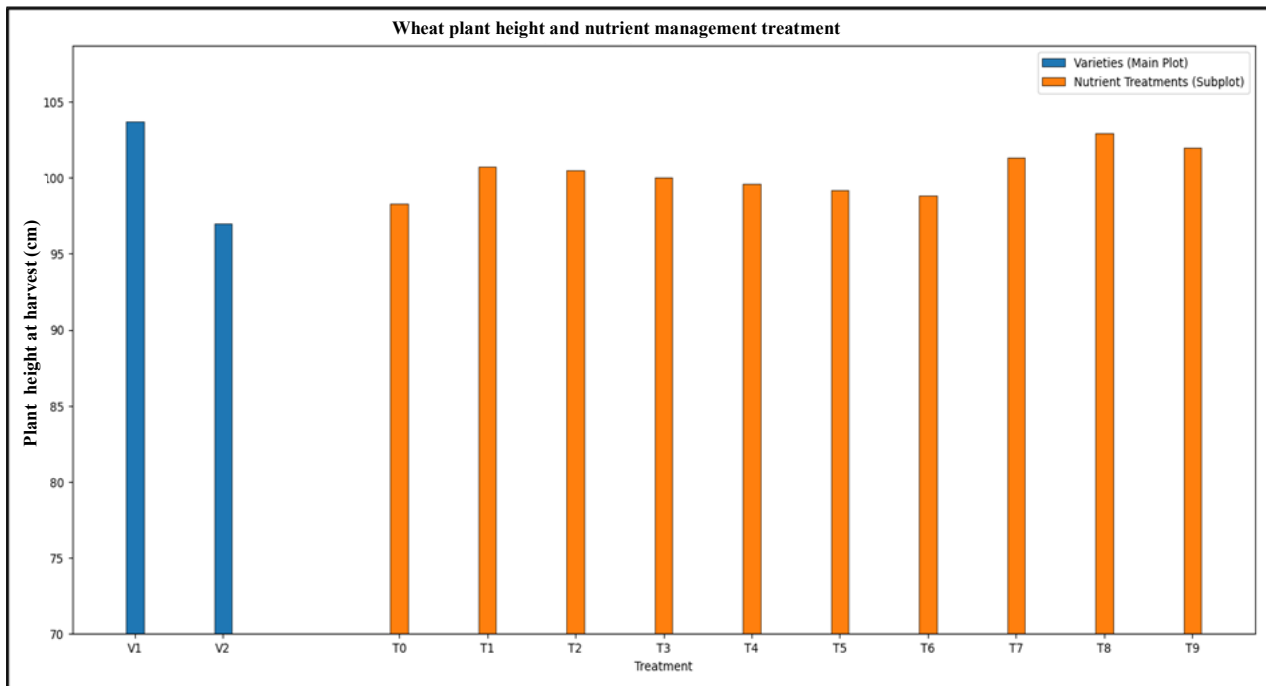


Fig. 1. Plant height at harvest (cm) (at pooled).

Table 1. Plant height (cm)

Treatments	45 DAS			60 DAS			90 DAS			harvest stage		
	2022–23	2023–24	Pooled	2022–23	2023–24	Pooled	2022–23	2023–24	Pooled	2022–23	2023–24	Pooled
Wheat varieties (V)												
V ₁	35.9	36.6	36.3	57.4	58.1	57.7	92.1	92.9	92.5	103.1	104.3	103.7
V ₂	32.7	33.4	33.0	50.4	51.1	50.7	87.9	88.6	88.3	96.5	97.4	97.0
SE(m) ±	0.06	0.03	0.02	0.05	0.06	0.05	0.06	0.05	0.07	0.68	0.55	0.21
CD (p = 0.05)	0.43	0.22	0.16	0.37	0.39	0.34	0.37	0.36	0.49	4.44	3.63	1.39
Nutrient management (T)												
T ₀	32.5	33.1	32.8	51.5	52.2	51.8	87.6	88.3	87.9	97.7	98.9	98.3
T ₁	34.6	35.2	34.9	54.4	55.1	54.7	90.6	91.2	90.9	100.4	101.1	100.7
T ₂	34.4	35.1	34.7	54.2	54.9	54.5	90.3	91.0	90.6	100.0	101.0	100.5
T ₃	34.0	34.6	34.3	53.7	54.4	54.1	89.8	90.5	90.2	99.4	100.6	100.0
T ₄	33.9	34.5	34.2	53.4	54.1	53.7	89.4	90.1	89.7	99.0	100.3	99.6
T ₅	33.5	34.1	33.8	52.8	53.4	53.1	88.6	89.3	89.0	98.7	99.8	99.2
T ₆	33.0	33.7	33.3	52.2	52.9	52.5	88.2	88.9	88.6	98.3	99.3	98.8
T ₇	34.8	35.5	35.1	54.7	55.4	55.0	90.9	91.6	91.3	100.9	101.7	101.3
T ₈	36.9	37.6	37.2	56.7	57.3	57.0	93.1	93.8	93.4	102.1	103.6	102.9
T ₉	35.7	36.3	36.0	55.4	56.1	55.7	91.9	92.6	92.3	101.4	102.5	102.0
SE(m) ±	0.18	0.19	0.16	0.26	0.25	0.26	0.20	0.21	0.21	1.08	0.88	0.71
CD (p = 0.05)	0.51	0.55	0.48	0.76	0.75	0.76	0.60	0.61	0.61	3.03	2.54	2.04
Interaction (V × T)												
SE(m) ±	0.21	0.11	0.08	0.18	0.18	0.19	0.18	0.17	0.23	2.15	1.75	0.67
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

DAS = Days after sowing; RDF= Recommended dose of fertilisers; NS= non-significant.

103.7 cm based on pooled analysis. Similarly, among the nutrient management treatments, T₈ recorded the maximum plant height of 102.9 cm, followed by T₉(102.0 cm) and T₇ (101.3 cm), which is also evident from the comparative heights of the bars in the graph. However, interaction effect was found to be non-significant among all the cropping seasons.

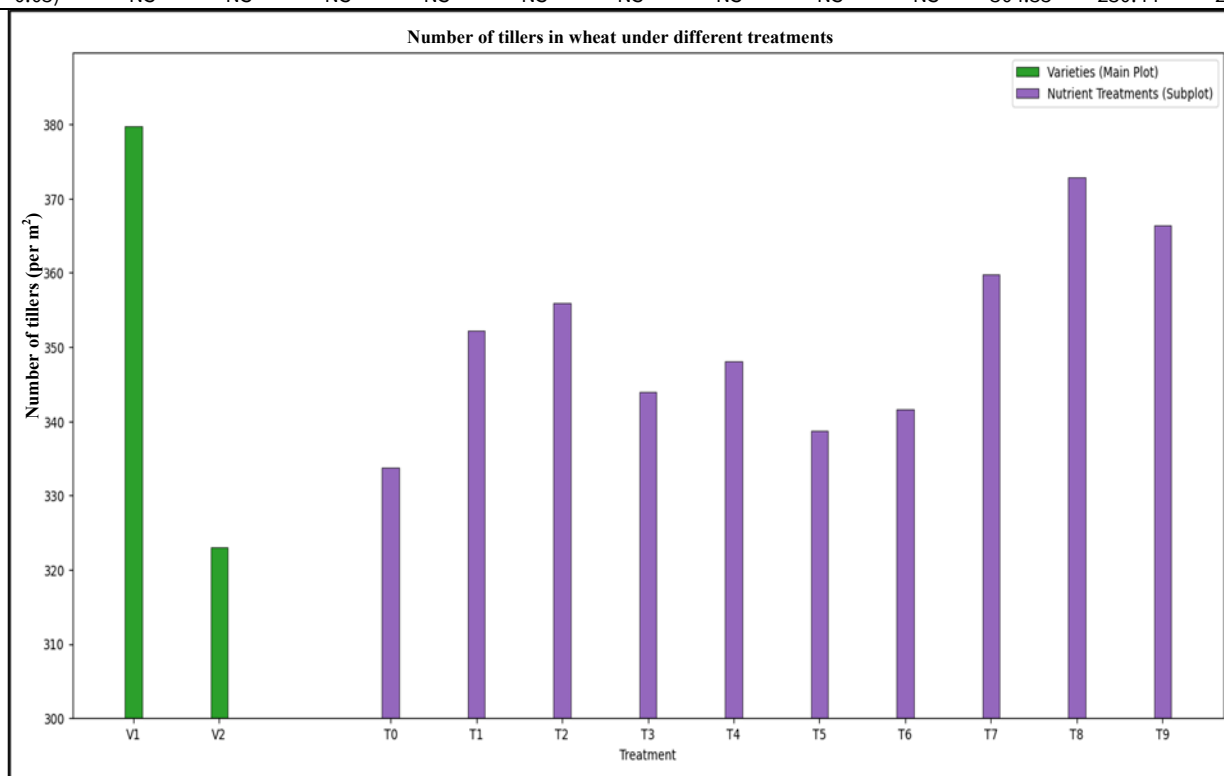
It was also reported that zinc and iron applications significantly boosted plant height due to improved nutrient assimilation, while copper further enhanced metabolic activities responsible for growth promotion (22). Additionally, it was found that balanced soil-applied micronutrients facilitated better root development and nutrient absorption, ultimately leading to increased vegetative growth in wheat (23–26). Similarly, another research work highlighted that Zn and Fe markedly increased wheat plant height during mid to late vegetative growth stages by stimulating auxin biosynthesis, photosynthetic activity and cell elongation (27).

Number of tillers (sq m⁻¹)

The data for number of tillers/m² is given in Table 2 (Fig. 2). In the 2022–23 growing season, variety DBW-222 (380.86 tillers/m²) significantly outperformed variety HD-2967 (323.70 tillers/m²) in the number of tillers/m² which might be due to varietal potential. Among nutrient management treatments, the highest number of tillers (373.63) was observed under treatment (T₈), involving soil application of Zn + Fe+ Cu through ZnSO₄.7H₂O at 20 Kg ha⁻¹, FeSO₄.7H₂O at 12 Kg ha⁻¹, CuSO₄.5H₂O at 2.0 Kg ha⁻¹, followed by the treatment T₉, which involved foliar spray of Zn + Fe + Cu as 1.0 % ZnSO₄.7H₂O, 1.5 % FeSO₄.7H₂O and 0.1 % CuSO₄.5H₂O at tillering and booting stages (366.59). The lowest number of tillers (335.29) was recorded under the control treatment T₀. Soil-applied combined micronutrient treatment (T₈) produced 11.7 % more tillers than control (T₀) in pooled analysis. Similarly, T₉ and T₇ increased tiller number by 9.8 % and 7.8 % respectively over control. In the subsequent 2023–24 season, a similar trend was observed.

Table 2. Number of tillers, days to heading, days to maturity and grain yield

Treatments	Number of tillers (sq m ⁻¹)			Days to heading			Days to maturity			Grain Yield (kg ha ⁻¹)		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
Wheat varieties												
V ₁	380.86	378.54	379.69	84.2	85.1	84.7	131.3	132.9	132.1	6,172	6,107	6,139
V ₂	323.70	322.30	323.00	86.7	87.8	87.2	129.4	130.7	130.0	5,283	5,215	5,249
SE(m) ±	2.42	1.63	1.91	0.17	0.33	0.10	0.10	0.14	0.12	43.30	28.28	35.69
CD (p = 0.05)	15.88	10.69	12.54	1.14	2.12	0.70	0.71	0.93	0.81	283.71	185.26	233.82
Nutrient management												
T ₀	335.29	332.37	333.83	88.2	88.8	88.5	134.3	136.0	135.2	5,091	5,022	5,057
T ₁	352.97	351.58	352.28	86.3	87.3	86.8	132.7	134.0	133.3	5,847	5,778	5,812
T ₂	356.84	355.17	356.00	87.0	87.8	87.4	132.8	134.0	133.4	5,681	5,626	5,653
T ₃	345.08	342.70	343.89	85.6	86.6	86.1	131.3	132.8	132.1	5,601	5,528	5,564
T ₄	349.25	346.84	348.04	86.1	87.0	86.6	131.7	133.2	132.4	5,529	5,470	5,500
T ₅	339.72	337.77	338.75	84.9	85.9	85.4	129.3	130.8	130.1	5,464	5,403	5,434
T ₆	342.79	340.54	341.67	85.1	86.3	85.7	130.2	131.7	130.9	5,460	5,376	5,418
T ₇	360.64	359.03	359.83	84.4	85.5	84.9	128.3	129.7	129.0	6,073	6,003	6,038
T ₈	373.63	371.97	372.80	83.3	84.5	83.9	125.8	127.3	126.6	6,312	6,257	6,284
T ₉	366.59	366.22	366.41	83.7	84.9	84.3	126.8	128.5	127.7	6,213	6,144	6,179
SE(m) ±	3.24	2.50	1.72	1.00	0.91	0.74	0.27	0.37	0.31	57.10	46.47	37.55
CD (p = 0.05)	9.34	7.20	4.94	2.86	2.60	2.13	0.76	1.07	0.86	164.44	133.83	108.13
Interaction												
V × T	352.28	350.42	351.35	85.4	86.4	85.9	130.3	131.8	131.1	5,727	5,661	5,694
SE(m) ±	7.66	5.17	6.05	0.55	1.05	0.34	0.34	0.45	0.39	136.95	89.43	112.86
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	304.35	230.44	218.08

**Fig. 2.** Number of tillers (sq m⁻¹) (at pooled).

The pooled analysis of 2 years further confirmed the superior performance of DBW-222 (379.69 tillers/m²) compared to HD-2967 (323.00 tillers/m²). Among nutrient management practices, soil-applied combined micronutrients (T₈) resulted in the highest number of tillers (372.80) and the graph is depicted in Fig. 2. The lowest pooled tiller count (333.83) was observed in control plots receiving only the RDF. The improved tiller production under T₈ and T₉ can be explained by the combined application of micronutrients and their influence on hormonal balance, particularly the stimulation of auxins and cytokinins that promote tiller initiation and growth (28–30).

Days to heading

It is evident from Table 2 that, in the 2022–23 growing season, variety DBW-222 reached heading stage earlier at 84.2 DAS

compared to 86.7 days for HD-2967. This earlier heading in DBW-222 may be attributed to its inherent genetic make-up, which confers a shorter vegetative period and faster transition to the reproductive phase. DBW-222 is known for its early maturity traits and efficient utilisation of resources, which enable it to initiate flowering under similar agro-climatic conditions earlier than HD-2967 (IIWBR, Karnal). The differential response between these 2 varieties is likely due to variations in their photoperiod sensitivity, hormonal balance and enzymatic activities that regulate phenological development. Among nutrient management treatments, the earliest heading (83.3 days) was observed under treatment T₈, involving soil application of (Zn + Fe + Cu) through ZnSO₄·7H₂O at 20 Kg ha⁻¹, FeSO₄·7H₂O at 12 Kg ha⁻¹, CuSO₄·5H₂O at 2.0 Kg ha⁻¹, followed by treatment (T₉) involving foliar application of (Zn + Fe + Cu) as 1.0 % ZnSO₄·7H₂O, 1.5 %

$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ and 0.1 % $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ at tillering and booting stages where heading was observed at 83.7 days. The latest heading was recorded under the control treatment T_0 (88.2 days). Same trend was also observed in the 2023–24 season.

The pooled analysis of 2 years further confirmed the superior phenological performance of DBW-222 (84.7 days) compared to HD-2967 (87.2 days) as depicted in Fig. 3. Among nutrient management practices, soil-applied combined micronutrients (T_8) resulted in the earliest heading (83.9 days), followed by treatment (T_9) where heading was observed at 84.3 days. The latest pooled heading (88.5 days) was observed in control plots receiving only the RDF. However, the interaction effect was found to be non-significant during the experimental period. The advancement in heading observed under T_8 and T_9 treatments may be attributed to improved micronutrient availability, especially zinc, iron and copper, which play crucial roles in various enzymatic and hormonal activities involved in floral initiation. Zinc is essential for auxin biosynthesis and protein metabolism, iron is a key component in chlorophyll synthesis and redox reactions and copper is involved in lignification and reproductive development. Their combined or foliar application likely enhanced physiological efficiency and accelerated phenological development, resulting in earlier heading (31, 32).

Days to maturity

The data for days to maturity is given in Table 2. In the 2022–23 growing season, variety DBW-222 took 131.3 days to mature, compared to 129.4 days for HD-2967. Among nutrient management treatments, the earliest maturity (125.8 days) was observed under T_8 , involving soil application of (Zn + Fe + Cu) through $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ at 20 Kg ha^{-1} , $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ at 12 Kg ha^{-1} , $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ at 2.0 Kg ha^{-1} , followed by T_9 , where these micronutrients were applied as foliar sprays (126.8 days). This earliness in maturity due to micronutrient application, particularly under T_8 and T_9 , can be attributed to improved nutrient availability enhancing physiological and metabolic processes that govern reproductive development and grain filling. The latest maturity was recorded under the control treatment T_0 (134.3 days). Among the individual application of micronutrient fertilisers, copper sulphate resulted in earliest maturity followed by iron sulphate and zinc sulphate.

Copper plays a significant role in accelerating reproductive growth by influencing pollen viability, enzyme activation and lignin synthesis, thereby hastening the maturation process. Furthermore, the earlier maturity observed in HD-2967 may be linked to its varietal trait of shorter crop duration under certain conditions. In contrast, DBW-222, though a high-yielding variety, exhibits a slightly longer maturity period, possibly due to extended grain filling duration and higher biomass accumulation. The combined application of micronutrients (T_8 and T_9) appears to harmonise and accelerate the physiological processes involved in the plant's life cycle, thereby reducing the days to maturity compared to untreated control plots. Same trend was also observed in the 2023–24 season.

The pooled analysis of 2 years further confirmed that DBW-222 matured later (132.1 days) compared to HD-2967 (130.0 days) as depicted in Fig. 3. Among nutrient management practices, soil-applied combined micronutrients (T_8) resulted in the earliest maturity (126.6 days), while foliar application of these nutrients (T_9) was the second-best treatment (127.7 days). The latest pooled maturity (135.2 days) was observed in control plots receiving only the RDF. The earlier maturity in T_8 and T_9 treatments could be attributed to enhanced assimilate translocation and improved metabolic efficiency under better micronutrient availability (29).

Grain yield

The data pertaining to grain yield is presented in Table 2 and graphically presented in Fig. 4. The variety DBW-222 significantly outperformed HD-2967 in terms of grain yield during both the years as well as in pooled analysis. On pooled basis, variety DBW-222 recorded a grain yield of 6139 kg ha^{-1} , whereas variety HD-2967 recorded 5249 kg ha^{-1} .

Among the nutrient management treatments, the maximum grain yield was observed under T_8 (RDF + soil application of Zn + Fe + Cu through $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ at 20 kg ha^{-1} , $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ at 12 kg ha^{-1} , $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ at 2.0 kg ha^{-1}), which produced the highest pooled grain yield of 6284 kg ha^{-1} , followed by T_9 (RDF + foliar application of Zn + Fe + Cu through 1.0 % $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 1.5 % $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ and 0.1 % $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ at tillering and booting stages) with

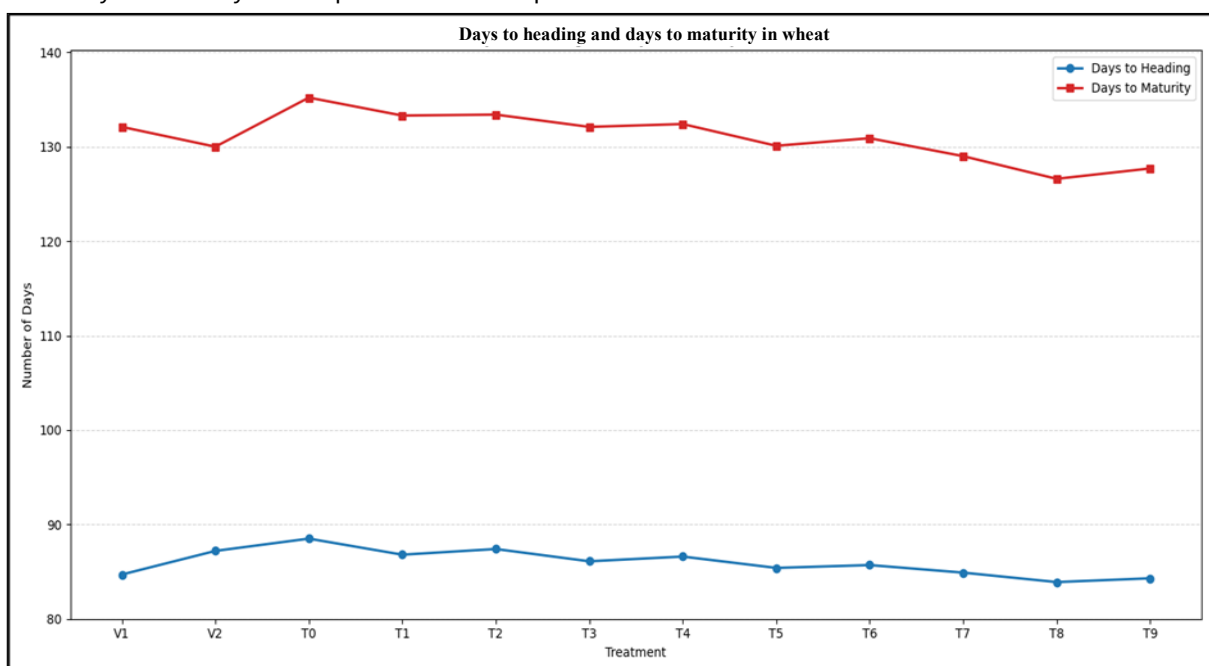


Fig. 3. Days to heading and days to maturity (at pooled).

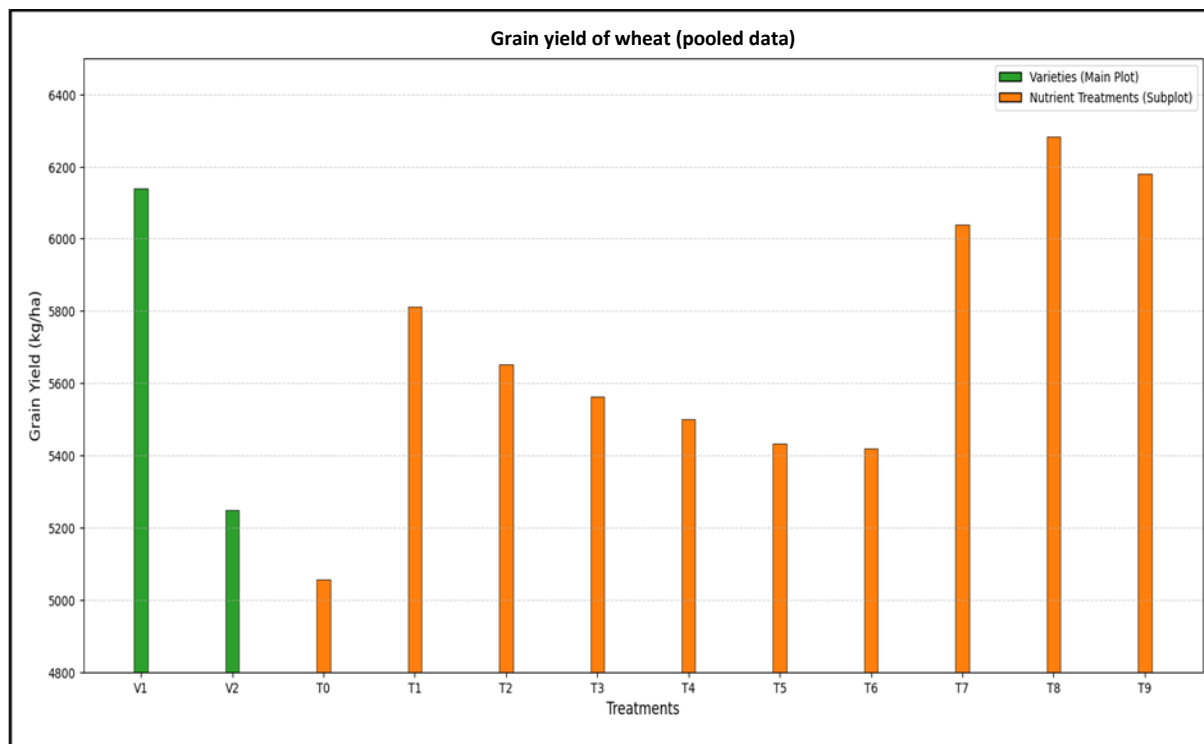


Fig. 4. Grain yield (kg ha^{-1}) (at pooled).

6179 kg ha^{-1} and T_7 (RDF + foliar spray of Zn + Fe) with 6038 kg ha^{-1} . The lowest grain yield (5057 kg ha^{-1}) was recorded under the control treatment (T_0). However, the interaction effect between varieties and nutrient management treatments ($V \times T$) on grain yield was also found to be significant during both the years as well as in pooled analysis.

Dry matter production (DMP)

The data for dry matter production is given in Table 3. At 45 DAS, the pooled analysis of 2 years further confirmed the superior biomass production of DBW-222 (159 g m^{-2}) compared to HD-2967 (154.4 g m^{-2}). Among nutrient management practices, soil-applied combined micronutrients (T_8) resulted in the highest dry matter production (166 g m^{-2}), followed by soil-applied zinc alone (T_1) at 163.1 g m^{-2} . The slightly higher DMP in T_1 compared to T_3 suggests that zinc had a more pronounced effect on early growth compared

to iron when applied individually. This aligns with the earlier findings (33, 34), which reported that zinc application significantly enhances early vegetative growth and shoot biomass in wheat due to its involvement in enzyme activation and hormone regulation. Pooled data revealed consistently higher biomass in DBW-222 than HD-2967 at all growth stages. At 60 DAS, DBW-222 recorded 424.41 g m^{-2} compared to 407.84 g m^{-2} in HD-2967. Soil-applied combined micronutrients (T_8) produced the highest dry matter (482.1 g m^{-2}), followed by combined foliar application (T_5 ; 471.89 g m^{-2}), whereas control (RDF alone) recorded the lowest (337.64 g m^{-2}). At 90 DAS, biomass increased sharply, with DBW-222 (1349.30 g m^{-2}) outperforming HD-2967 (1295.45 g m^{-2}) and T_8 registering the maximum dry matter (1527.05 g m^{-2}), confirming the superiority of combined micronutrient application. The same trend continued at 120 DAS.

Table 3. Dry matter production (DMP) (g m^{-2})

Treatments	45 DAS			60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
Wheat varieties												
V ₁	158.0	160.0	159.0	418.82	429.99	424.41	1,334.31	1,364.29	1,349.30	1,595.38	1,596.09	1,595.73
V ₂	153.4	155.4	154.4	402.56	413.11	407.84	1,294.39	1,296.51	1,295.45	1,531.13	1,533.51	1,532.32
SE(m) ±	0.21	0.16	0.04	1.51	1.79	1.67	5.69	0.63	2.96	10.06	1.10	4.81
CD ($p = 0.05$)	1.42	1.09	0.24	9.89	11.73	10.91	37.26	4.12	19.42	65.89	7.20	31.50
Nutrient management												
T ₀	151.7	153.4	152.6	331.95	343.33	337.64	1,061.42	1,077.03	1,069.22	1,265.43	1,272.91	1,269.17
T ₁	162.0	164.3	163.1	434.68	447.57	441.13	1,393.44	1,414.72	1,404.08	1,662.34	1,662.52	1,662.43
T ₂	152.0	153.7	152.9	420.41	430.94	425.67	1,349.88	1,360.80	1,355.34	1,599.00	1,592.86	1,595.93
T ₃	160.0	162.2	161.1	405.25	415.44	410.35	1,296.70	1,310.64	1,303.67	1,539.99	1,550.43	1,545.21
T ₄	151.9	153.6	152.7	391.31	400.49	395.90	1,249.48	1,262.20	1,255.84	1,483.07	1,474.15	1,478.61
T ₅	158.5	160.6	159.6	373.53	384.92	379.22	1,202.53	1,211.78	1,207.16	1,423.77	1,420.28	1,422.03
T ₆	152.2	153.9	153.0	353.38	365.59	359.49	1,152.31	1,149.14	1,150.72	1,350.17	1,363.48	1,356.83
T ₇	152.0	153.8	152.9	452.56	463.13	457.84	1,436.72	1,465.05	1,450.89	1,721.56	1,738.69	1,730.13
T ₈	164.8	167.2	166.0	476.73	487.47	482.10	1,510.17	1,543.92	1,527.05	1,814.25	1,808.27	1,811.26
T ₉	152.0	154.0	153.0	467.16	476.63	471.89	1,490.86	1,508.73	1,499.80	1,772.97	1,764.42	1,768.70
SE(m) ±	0.34	0.36	0.23	4.31	4.77	3.56	11.55	12.72	8.79	15.29	17.31	13.31
CD ($p = 0.05$)	0.97	1.05	0.68	12.42	13.73	10.25	33.28	36.62	25.31	44.02	49.85	38.34
Interaction												
SE(m) ±	0.68	0.52	0.12	4.77	5.66	5.27	17.99	1.99	9.37	31.80	3.47	15.21
CD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

DAS = Days after sowing.

Zinc plays a crucial role in protein synthesis and auxin metabolism, promoting cell division and elongation. Iron is involved in chlorophyll formation and energy transfer processes in photosynthesis (20, 32). Their combined availability through soil application ensures optimal root development, leaf expansion and early biomass production.

Crop growth rate (CGR)

The data pertaining to crop growth rate (CGR) at 0–45 and 30–60 DAS is presented in Table 4. The variety DBW-222 recorded significantly higher CGR compared to HD-2967 during both the years as well as in pooled analysis. On pooled basis, DBW-222 recorded highest CGR of 3.533 g m⁻² day⁻¹ at 0–45 DAS and 12.847 g m⁻² day⁻¹ at 30–60 DAS, whereas HD-2967 recorded 3.430 g m⁻² day⁻¹ and 12.450 g m⁻² day⁻¹ respectively. Among the nutrient management treatments, the highest CGR values at both growth intervals were obtained under T₈ (RDF + soil application of Zn + Fe + Cu through ZnSO₄·7H₂O at 20 kg ha⁻¹, FeSO₄·7H₂O at 12 kg ha⁻¹, CuSO₄·5H₂O at 2.0 kg ha⁻¹), which recorded pooled CGR of 3.689 g m⁻² day⁻¹ at 0–45 DAS and 14.537 g m⁻² day⁻¹ at 30–60 DAS. This was followed by T₉ (RDF + foliar application of Zn + Fe + Cu as 1.0 % ZnSO₄·7H₂O, 1.5 % FeSO₄·7H₂O and 0.1 % CuSO₄·5H₂O at tillering and booting stages), which recorded 3.400 g m⁻² day⁻¹ and 14.630 g m⁻² day⁻¹ at the respective stages. The lowest CGR values (3.390 g m⁻² day⁻¹ at 0–45 DAS and 10.170 g m⁻² day⁻¹ at 30–60 DAS) were recorded under the control treatment (T₀). At this stage, the root system is actively developing and the steady availability of essential elements like zinc (involved in cell division and auxin synthesis), iron (critical for chlorophyll formation and energy transfer) and copper (important for lignin synthesis and enzymatic functions) enhances photosynthetic activity and tissue expansion. In contrast, foliar sprays may not be as effective in the early phase due to limited leaf surface area, reduced absorption efficiency and shorter nutrient retention time, resulting in minimal impact on CGR.

It is evident from the Table 4 that, the period of 60–90 DAS corresponds to the active vegetative and critical reproductive

phase, during which wheat exhibits peak biomass accumulation, resulting in the highest CGR values across the crop cycle. In the 2022–23 season, variety DBW-222 recorded a higher CGR (30.516 g m⁻² day⁻¹) than HD-2967 (29.728 g m⁻² day⁻¹) and a similar trend was observed in 2023–24 (31.143 vs 29.447 g m⁻² day⁻¹), with the pooled analysis confirming the superiority of DBW-222 (30.830 g m⁻² day⁻¹) over HD-2967 (29.587 g m⁻² day⁻¹). At pooled, among nutrient management treatments, the highest CGR (34.832 g m⁻² day⁻¹) was observed under T₈, involving soil application of (Zn + Fe + Cu) through ZnSO₄·7H₂O at 20 Kg ha⁻¹, FeSO₄·7H₂O at 12 Kg ha⁻¹, CuSO₄·5H₂O at 2.0 Kg ha⁻¹, followed closely by T₉ (34.264 g m⁻² day⁻¹), where combined nutrients were applied as a foliar spray. The foliar spray of Zn + Fe (T₇) also resulted in a substantial increase (33.101 g m⁻² day⁻¹), clearly outperforming all individual micronutrient applications. While foliar applications (T₇ and T₉) showed a rapid response due to direct nutrient absorption through leaf surfaces, soil application (T₈) sustained nutrient availability over a longer period, thereby supporting continuous root uptake and physiological activity throughout the growth.

It is evident from the Table 4 that, the period of 90–120 DAS shows the transition from active vegetative growth to reproductive maturity, during which CGR naturally declines due to reduced photosynthetic activity, leaf senescence and translocation of assimilates toward grain filling. The overall decline in CGR during 90–120 DAS is consistent with physiological expectations, as nutrient demand decreases and assimilates are redirected to developing grains. However, the significantly higher values under combined Zn, Fe and Cu treatments demonstrate that maintaining micronutrient availability through this stage helps sustain metabolic processes critical for grain filling. These findings are in tune with the earlier report (35, 36) which revealed that micronutrient application prolonged effective photosynthesis and delayed senescence, thereby moderating the rate of CGR decline during crop maturity. Higher CGR under combined micronutrient application indicates improved photosynthetic efficiency and assimilate partitioning.

Table 4. Crop growth rate (CGR) (g m⁻² day⁻¹)

Treatments	0–45 DAS			30–60 DAS			60–90 DAS			90–120 DAS		
	2022–23	2023–24	Pooled	2022–23	2023–24	Pooled	2022–23	2023–24	Pooled	2022–23	2023–24	Pooled
Wheat varieties												
V ₁	3.512	3.555	3.533	12.693	13.000	12.847	30.516	31.143	30.830	8.702	7.727	8.214
V ₂	3.408	3.452	3.430	12.307	12.592	12.450	29.728	29.447	29.587	7.891	7.900	7.896
SE(m) ±	0.005	0.004	0.002	0.056	0.058	0.056	0.159	0.059	0.079	0.232	0.034	0.099
CD (p = 0.05)	0.03	0.025	0.012	0.365	0.377	0.369	NS	0.384	0.515	NS	NS	NS
Nutrient management												
T ₀	3.371	3.409	3.390	10.009	10.330	10.170	24.316	24.457	24.386	6.800	6.529	6.665
T ₁	3.600	3.650	3.625	13.090	13.444	13.267	31.959	32.238	32.098	8.963	8.260	8.612
T ₂	3.378	3.416	3.397	12.948	13.240	13.094	30.982	30.995	30.989	8.304	7.735	8.020
T ₃	3.555	3.604	3.579	12.176	12.443	12.309	29.715	29.840	29.778	8.110	7.993	8.051
T ₄	3.375	3.413	3.394	11.982	12.230	12.106	28.606	28.724	28.665	7.787	7.065	7.426
T ₅	3.522	3.569	3.546	11.168	11.478	11.323	27.634	27.562	27.598	7.375	6.950	7.162
T ₆	3.381	3.421	3.401	10.707	11.056	10.882	26.631	26.118	26.375	6.596	7.145	6.870
T ₇	3.378	3.417	3.398	14.018	14.312	14.165	32.806	33.397	33.101	9.495	9.121	9.308
T ₈	3.662	3.716	3.689	14.399	14.675	14.537	34.448	35.215	34.832	10.136	8.812	9.474
T ₉	3.379	3.421	3.400	14.504	14.756	14.630	34.124	34.404	34.264	9.404	8.523	8.963
SE(m) ±	0.007	0.008	0.005	0.145	0.160	0.120	0.390	0.441	0.319	0.722	0.718	0.568
CD (p = 0.05)	0.021	0.023	0.015	0.419	0.460	0.345	1.124	1.271	0.919	2.078	NS	1.636
Interaction												
SE(m) ±	0.015	0.012	0.006	0.176	0.182	0.178	0.502	0.185	0.249	0.734	0.107	0.314
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

DAS = Days after sowing.

Conclusion

Based on the findings of the current study, it can be concluded that the combined soil application of zinc sulphate, iron sulphate and copper sulphate fertilisers significantly enhanced the growth and development of wheat compared to individual applications. Individually applied micronutrient fertilisers were found to be less effective in meeting the nutrient requirements of the crop and failed to produce consistent improvements in agronomic traits. Although foliar application of these micronutrients also showed positive effects, the results were inferior to those of the soil-applied combination. The synergistic effect of soil-applied micronutrients contributed to enhanced plant height, increased tillers and overall crop vigour under field conditions. The combined soil application of ZnSO₄, FeSO₄ and CuSO₄ significantly improved plant height, tillering, dry matter production and crop growth rate in wheat compared with individual or foliar applications. These results demonstrate the synergistic role of sulphate-based micronutrients in promoting wheat growth and development under field conditions.

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Authors' contributions

Investigation was carried out by DSS. Conceptualisation was done by DSS, BS and SS. Data curation was performed by DSS and APS, while laboratory analysis and methodology were conducted by DSS. Resources were provided by JS, YPS and PS. Writing of the manuscript was done by DSS and manuscript reviewing and editing were carried out by DSS and JS. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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