

Original Research Article

EFFECT OF DIFFERENT SOURCES AND LEVELS OF ZINC ON THE NUTRIENT CONTENT, UPTAKE AND FERTILITY STATUS OF WHEAT

ABSTRACT:

A field study entitled "Effect of different sources and levels of zinc on the nutrient content, uptake and fertility status of wheat" was conducted during Rabi 2021-2022 at Wheat Research Unit, Dr.Panjabrao Deshmukh Krishi Vidyapeeth, Akola. The experimental soil collected from the wheat research unit field was slightly alkaline in reaction, medium in organic carbon, moderately calcareous, low in available N, medium in available P, remarkably high in available K, marginal in available S, and sufficient in micronutrients but deficient in Zn. The nine treatments T1 to T9 are applied in the plots in Randomized Block Design with three replications.

The higher nutrient content and N, P, K, S, Zn, Fe, Cu, and Mn uptake was recorded with the soil application of RDF + soil application of $\text{ZnSO}_4 @ 30 \text{ kg ha}^{-1}$.

It is concluded that the soil application of $\text{ZnSO}_4 @ 30 \text{ kg ha}^{-1}$ along with a recommended dose of fertilizer (RDF) at the time of sowing recorded the highest nutrient content, nutrient uptake and improvement in soil fertility.

Keywords: Wheat, Nutrient content, Uptake, Fertility status, Zinc different sources.

1. INTRODUCTION

Wheat (*Triticum aestivum L.*) is an annual plant of the Poaceae family. It is the most widely cultivated staple food crop in the world. It is the second particularly important food crop consumed next to rice and contributes to the extent of 25 per cent of the total food grain production of the country. Wheat is called as "King of cereals." The main species of wheat are common wheat (*Triticum aestivum L.*), Durum wheat (*Triticum durum Desf.*), and Emmer wheat (*Triticum dicoccum Schrank*). Wheat is a rich source of carbohydrates, protein, minerals, and vitamins. In India, more than 87 per cent of the total area of the crop brought in the green revolution and paved the way for food security in India. Wheat compares well with other important cereals in their nutritive value. It contains more protein than other cereals. Wheat has a relatively high content of 'niacin' and 'thiamine'. Wheat proteins are of special significance. Wheat provides 'gluten' which is used for supplying a structural framework for the familiar spongy, cellular texture of bread and other bakery products. Wheat is a cheap source of amino acids, whole wheat preparations supply a significant amount of Fe, P, Mg, Mn, Cu, Zn and vitamin B. Worldwide more land is devoted to the production of wheat than any other crop. The USA, Russia, China, Australia, Germany, France, Argentina and India are the main wheat-producing countries.

Katkaret *et al.* (2013) experimented and give district-wise deficiency of micronutrients in Vidarbha. In all 498 soil samples were collected from 83 villages in 07 tehsils from the Akola districts where Akola shows 70.5% Zn deficiency.

2. MATERIAL AND METHODS

The field experiment was conducted at the Wheat Research Unit, Dr.Panjabrao Deshmukh Krishi Vidyapeeth, Akola, during the rabi season 2021 – 22. Akola is situated in the subtropical zone and is located at the latitude of 20° 70' 02" North and longitude of 77° 00' 81" East, at an altitude of 307.42 m above mean sea level (MSL). The experimental field is situated at the latitude of 20° 41' 36.2" North and longitude 77° 02' 07.5" East at the altitude of 30.78 m above mean sea level (MSL).

Plant nutrient content was determined by washing samples with tap and distilled water, followed by drying in shade and then in a hot air oven at 64°C to a constant weight. The dried samples were ground using an electric grinder, stored in labelled polythene bags, and used for nutrient analysis.

Nutrient uptake for N, P, and K was calculated using grain and dry matter yield at harvest and nutrient concentration in the respective plot: Uptake (kg ha^{-1}) = (Nutrient content (%) \times Grain or straw yield (kg ha^{-1})) / 100. For micronutrients (Zn, Fe, Cu, Mn), the formula used was: Uptake (g ha^{-1}) = (Nutrient content (%) \times Grain or straw yield (kg ha^{-1})) / 1000.

Soil samples were collected (0-20 cm depth) from each treatment plot after wheat harvest. Samples were air-dried in shade, crushed to break clods, and sieved (2 mm) for analysis. For organic carbon, samples were further sieved (0.5 mm). The sieved material was used for determining various factors.

List 1- Treatment details:

T₁	The recommended dose of fertilizer (RDF) is 80:40:40 NPK kg ha^{-1}
T₂	RDF + Soil application of ZnSO_4 @ 15 kg ha^{-1}
T₃	RDF + Soil application of ZnSO_4 @ 30 kg ha^{-1}
T₄	RDF + Soil application of Zn EDTA @ 1.5 kg ha^{-1}
T₅	RDF + Soil application of Zn EDTA @ 3.0 kg ha^{-1}
T₆	RDF + Foliar application of ZnSO_4 @ 0.5% at CRI, tillering and milking stage
T₇	RDF + Foliar application of ZnSO_4 @ 1.0% at CRI, tillering and milking stage
T₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage
T₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage

Table 1: Initial soil properties of the experimental site

Sr. No.	Particular	Values
A. Soil properties		
1.	Soil pH (1:2.5)	8.29
2.	Electrical conductivity (ds m^{-1})	0.33
3.	Organic carbon (%)	0.47
4.	Calcium carbonate (%)	5.75
B. Fertility analysis		
1.	Available nitrogen (kg ha^{-1})	192.34
2.	Available phosphorous (kg ha^{-1})	11.17
3.	Available potassium (kg ha^{-1})	300.65
4.	Available Sulphur (mg kg^{-1})	10.22
5.	DTPA extractable Zn (mg kg^{-1})	0.49
6.	DTPA extractable Fe (mg kg^{-1})	5.57
7.	DTPA extractable Cu (mg kg^{-1})	3.47
8.	DTPA extractable Mn (mg kg^{-1})	4.51

3. RESULTS AND DISCUSSION

3.1 Effect of different sources and levels of zinc on the content and uptake of nutrient at different growth stages of wheat

3.1.1 Nitrogen Content

The results in relation to nitrogen content in wheat at different growth stages are reported in Table 2.

At 60 DAS, the highest nitrogen content (0.82%) was observed in T₃ (RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹), attributed to increased nitrogen availability due to zinc application. Other treatments showed similar nitrogen content, except for T₁ (RDF: 80:40:40 NPK kg ha⁻¹), which recorded the lowest value (0.72%). Differences among treatments at this stage were statistically non-significant.

At 90 DAS, a similar trend was observed, with T₃ showing the highest nitrogen content (0.77%) and T₁ the lowest (0.70%). However, the treatments remained statistically non-significant at this stage.

At the harvest stage, the nitrogen content in straw varied significantly across treatments. T₃ recorded the highest nitrogen content (0.75%) in straw, which was statistically at par with T₂, T₄, T₅, and T₇. The lowest nitrogen content (0.55%) was observed in T₁, likely due to limited nutrient availability. Nitrogen content in straw at harvest was lower than at 90 DAS, possibly due to reduced dry matter accumulation at harvest compared to earlier growth stages.

For grains at harvest, T₃ again recorded the highest nitrogen content (2.22%), followed by T₂, T₄, T₅, T₆, and T₇, all of which were statistically at par. The lowest nitrogen content (1.83%) was observed in T₁. Overall, nitrogen content in grains was significantly higher than in straw.

The results were in agreement with the findings reported by Shivay *et al.* (2008), Abbas *et al.* (2009), Cakmak *et al.* (2010), Prajapati *et al.* (2023) and Yadav *et al.* (2024). which reported that zinc application enhances nitrogen content in plants.

Table 2. Effect of different sources and levels of zinc on the content of nitrogen in wheat

Treatments	At 60 DAS (%)	At 90 DAS (%)	At harvest	
			Straw (%)	Grain (%)
T ₁ RDF (Control)	0.72	0.70	0.55	1.83
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	0.77	0.76	0.70	2.20
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	0.82	0.77	0.75	2.22
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	0.76	0.74	0.67	2.18
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	0.79	0.76	0.73	2.21
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	0.74	0.73	0.57	2.12
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	0.75	0.74	0.61	2.14
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	0.74	0.73	0.58	1.89
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	0.73	0.71	0.57	1.85

SE (m)±	0.045	0.045	0.047	0.099
CD at 5%	NS	NS	0.140	0.297

3.1.2 Nitrogen Uptake

The data in respect of N uptake by wheat grain and straw and total N uptake by wheat were significantly influenced by various treatments in Table 3.

Nitrogen uptake by wheat grain was significantly higher (95.88 kg ha⁻¹) with the soil application of RDF + ZnSO₄ @ 30 kg ha⁻¹ (T3), which was at par with RDF + soil application of Zn EDTA @ 3.0 kg ha⁻¹ (T5), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T2), RDF + soil application of Zn EDTA @ 1.5 kg ha⁻¹ (T4), and RDF + foliar application of ZnSO₄ @ 1.0% at CRI, tillering, and milking stages (T7). The lowest grain nitrogen uptake (66.02 kg ha⁻¹) was recorded in the recommended dose of fertilizer (RDF: 80:40:40 NPK kg ha⁻¹, T1).

Similarly, the highest nitrogen uptake by wheat straw (48.50 kg ha⁻¹) was observed in T3 and was at par with T5, T2, and T4. The lowest nitrogen uptake by straw (29.22 kg ha⁻¹) occurred in T1. The total nitrogen uptake by wheat was also significantly highest (144.38 kg ha⁻¹) in T3 and at par with T5, T2, and T4. The lowest total nitrogen uptake (95.24 kg ha⁻¹) was recorded in T1.

The increased nitrogen uptake with higher zinc application levels is likely due to the synergistic interaction between nitrogen and zinc, enhancing plant vegetative growth and nutrient assimilation. The soil application of zinc consistently resulted in higher grain, straw, and total nitrogen uptake compared to other treatments. These findings align with previous studies by Abbas *et al.* (2009), Keramet *et al.* (2014), Prajapati *et al.* (2023) and Yadav *et al.* (2024).

Table 3. Effect of different sources and levels of zinc on the uptake of nitrogen by wheat

Treatments	Nitrogen uptake (kg ha ⁻¹)			
	Grain	Straw	Total	
T ₁ RDF (Control)	66.02	29.22	95.24	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	91.79	43.43	135.23	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	95.88	48.50	144.38	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	89.78	41.64	131.42	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	93.27	46.50	139.78	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	78.62	31.13	109.75	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	80.21	33.45	113.66	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	68.12	31.05	99.18	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	67.09	30.30	97.40	
	SE (m)±	6.13	3.04	7.45
	CD at 5%	18.38	9.11	22.35

3.1.3 Phosphorous Content

The data in respect of the content of P in wheat at different stages were presented in Table 4. At 60 DAS, phosphorus content in wheat straw was significantly influenced by treatments, ranging from 0.24% to 0.30%. The highest phosphorus content (0.30%) was recorded in RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3), which was at par with T5, T2, T4, and T7. The lowest content (0.24%) was observed in RDF (T1).

At 90 DAS, similar trends were observed, with phosphorus content in wheat straw ranging from 0.23% to 0.28%. The highest content (0.28%) was again recorded in T3, and the lowest (0.23%) in T1, with treatments T5, T2, T4, and T7 showing comparable values.

At the harvest stage, phosphorus content in wheat straw ranged from 0.17% to 0.20%. The maximum content (0.20%) was observed in T3 and T5, while the lowest (0.17%) was recorded in T1, T8, and T9.

In wheat grain, phosphorus content at the harvest stage varied from 0.25% to 0.29%. The highest content (0.29%) was observed in T3 and T5, while the lowest (0.25%) was found in T1, T8, and T9. Phosphorus content in the straw and grain at harvest was lower compared to 60 and 90 DAS, likely due to reduced dry matter content at the harvest stage compared to earlier growth stages.

Singh (1991) observed an antagonistic effect of phosphorus on zinc application, a trend also observed in the present study. However, soil application of zinc had less impact on phosphorus content reduction compared to foliar treatments, likely contributing to higher grain and straw yields in T3. These findings align with those of Alamet *et al.* (2000), Prajapati *et al.* (2023) and Yadav *et al.* (2024).

Table 4. Effect of different sources and levels of zinc on the content of Phosphorous in wheat

Treatments	At 60 DAS (%)	At 90 DAS (%)	At harvest		
			Straw (%)	Straw (%)	
T ₁ RDF (Control)	0.24	0.23	0.17	0.25	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	0.29	0.26	0.19	0.28	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	0.30	0.28	0.20	0.29	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	0.28	0.25	0.18	0.26	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	0.29	0.27	0.20	0.29	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	0.26	0.24	0.18	0.26	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	0.27	0.25	0.18	0.26	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	0.26	0.24	0.17	0.25	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	0.25	0.23	0.17	0.25	
	SE (m)±	0.012	0.012	0.010	0.011
	CD at 5%	0.037	0.035	NS	NS

3.1.4 Phosphorous Uptake

The data pertaining to the grain, straw and total uptake of phosphorous by wheat was presented in Table 5.

The data revealed that the highest phosphorus uptake by wheat grain (12.56 kg ha⁻¹) was observed in the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3) treatment, while the lowest uptake (9.15 kg ha⁻¹) was recorded in the RDF 80:40:40 NPK kg ha⁻¹ (T1) treatment.

Similarly, phosphorus uptake by wheat straw was significantly higher (13.22 kg ha⁻¹) in T3 and lowest (8.91 kg ha⁻¹) in T1.

The total phosphorus uptake (grain + straw) was also highest (25.78 kg ha⁻¹) in T3, whereas the lowest total uptake (18.06 kg ha⁻¹) was observed in T1.

Phosphorus content in grain was notably higher than in straw, likely because absorbed phosphorus is preferentially translocated and utilized in forming specific phosphorus compounds in the grain, leading to reduced phosphorus levels in the straw. These findings align with those reported by Kumar and Yadav (2005), Keramet *et al.* (2014), Prajapati *et al.* (2023) and Yadav *et al.* (2024).

Table 5. Effect of different sources and levels of zinc on uptake of phosphorous by wheat

Treatments	Phosphorous uptake (kg ha ⁻¹)			
	Grain	Straw	Total	
T ₁ RDF (Control)	9.15	8.91	18.06	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	11.66	11.98	23.64	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	12.56	13.22	25.78	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	10.64	11.18	21.82	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	12.05	13.01	25.06	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	9.47	9.73	19.20	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	9.69	9.99	19.68	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	9.14	9.08	18.22	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	9.04	8.97	18.01	
	SE (m)±	0.70	0.89	1.37
	CD at 5%	2.10	2.68	4.11

3.1.5 Potassium Content

The data pertaining to the content of potassium in wheat at different growth stages are reported in Table 6.

At 60 DAS, the potassium content in wheat straw was significantly higher (1.91%) in the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3) treatment. This was statistically at par with treatments such as RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T5), RDF + ZnSO₄ @ 15 kg ha⁻¹ (T2), RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T4), and RDF + foliar application of ZnSO₄ @ 1.0% at CRI, tillering, and milking stage (T7). The lowest potassium content (1.37%) was recorded in the RDF 80:40:40 NPK kg ha⁻¹ (T1) treatment.

At 90 DAS, a decrease in potassium content in wheat straw was observed compared to the 60 DAS stage. The highest potassium content (1.86%) was recorded in T3, which remained statistically at par with T5, T2, and T4. The lowest potassium content (1.20%) was again observed in the T1 treatment.

At the harvest stage, potassium content in wheat straw decreased further, likely due to reduced dry matter content at this stage compared to the grand growth stage. The highest potassium content (1.76%) was observed in T3, which was statistically at par with T5, T2, T4, and T7. The lowest potassium content (1.12%) was recorded in the T1 treatment.

Potassium content in wheat grain at the harvest stage was highest (0.54%) in T3, surpassing all other treatments, though it remained statistically at par with T5, T2, and T4. The lowest potassium content (0.42%) in grain was observed in T1.

The increase in potassium content in both grain and straw across growth stages can be attributed to the application of zinc, as observed in this study.

These findings align with those reported by Ghasalet *et al.* (2017) and Yadav *et al.* (2024).

Table 6. Effect of different sources and levels of zinc on the content of potassium in wheat

Treatments	At 60 DAS (%)	At 90 DAS (%)	At harvest		
			Straw (%)	Grain (%)	
T ₁ RDF (Control)	1.37	1.20	1.12	0.42	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	1.79	1.73	1.64	0.49	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	1.91	1.86	1.76	0.54	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	1.70	1.65	1.57	0.48	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	1.89	1.81	1.65	0.51	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	1.61	1.35	1.24	0.45	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	1.65	1.49	1.36	0.45	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	1.57	1.36	1.28	0.44	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	1.43	1.27	1.21	0.43	
	SE (m)±	0.09	0.08	0.07	0.02
	CD at 5%	0.28	0.23	0.22	0.07

3.1.6 Potassium Uptake

The data in Table 7 in respect of K uptake by wheat grain, straw and total K uptake by wheat were significantly influenced by various treatments.

The data indicated that potassium uptake by wheat grains was significantly higher (23.46 kg ha⁻¹) in the treatment with RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). This treatment was statistically at par with RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T₅), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T₂), and RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T₄). The lowest potassium uptake (14.91 kg ha⁻¹) in grain was observed in the RDF 80:40:40 NPK kg ha⁻¹ (T₁) treatment.

Potassium uptake by wheat straw was significantly highest (114.49 kg ha⁻¹) in T₃ and was statistically at par with T₅, T₂, and T₄. The lowest potassium uptake (59.56 kg ha⁻¹) in straw was recorded in the T₁ treatment.

Total potassium uptake by wheat was significantly highest (137.95 kg ha⁻¹) in T₃, which was statistically at par with T₅, T₂, and T₄. The lowest total potassium uptake (74.47 kg ha⁻¹) was observed in the T₁ treatment.

The results align with the findings of Pederson *et al.* (2002), Gul *et al.* (2011), Keramet *et al.* (2014), and Yadav *et al.* (2024). who reported that zinc sufficiency enhances potassium efflux from roots and shoots into the growth medium. Additionally, zinc facilitates the movement of potassium in the guard cells of stomata.

Table 7: Effect of different sources and levels of zinc on uptake of potassium by wheat

Treatments	Potassium uptake (kg ha ⁻¹)		
	Grain	Straw	Total
T ₁ RDF (Control)	14.91	59.56	74.47

T ₂	RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	20.25	101.96	122.22
T ₃	RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	23.46	114.49	137.95
T ₄	RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	19.77	96.84	116.61
T ₅	RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	21.63	107.15	128.78
T ₆	RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	16.77	68.19	84.97
T ₇	RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	16.97	74.34	91.31
T ₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	15.95	67.94	83.88
T ₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	15.84	64.43	80.27
SE (m)±		1.31	6.33	6.84
CD at 5%		3.93	18.99	20.51

3.1.7 Sulphur Content

The data pertaining to the content of sulphur in wheat at different growth stages are reported in Table 8.

The sulphur content in wheat straw at the 60 DAS stage was highest (0.16%) in the treatment of RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). This was statistically at par with treatments such as RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T₂), RDF + foliar application of ZnSO₄ @ 1.0% at CRI, tillering, and milking stage (T₇), and RDF + foliar application of ZnSO₄ @ 0.5% at CRI, tillering, and milking stage (T₆). The lowest sulphur content (0.10%) was observed in the RDF 80:40:40 NPK kg ha⁻¹ (T₁) treatment.

A significant decrease in sulphur content in wheat straw was observed at 90 DAS compared to 60 DAS. The maximum sulphur content (0.14%) was recorded in T₃, which was statistically at par with T₂, T₇, and T₆. The lowest sulphur content (0.09%) was observed in T₁.

At the harvest stage, sulphur content in wheat straw decreased compared to the content at 90 DAS, due to a reduction in dry matter at harvest. The highest sulphur content (0.13%) at harvest was observed in T₃, which was statistically at par with T₂, T₇, and T₆. The lowest sulphur content (0.08%) was recorded in T₁.

At harvest, sulphur content in wheat grain was highest (0.17%) in T₃, higher than all other treatments, but statistically at par with T₂, T₇, and T₆. The lowest sulphur content (0.11%) in grain was observed in T₁.

These results are consistent with the findings of Kumar and Singh (1979), Ravi *et al.* (2008), Kumar *et al.* (2010), Patil (2012) and Saralet *et al.* (2024).

Table 8. Effect of different sources and levels of zinc on the content of sulphur in wheat

Treatments	At 60 DAS (%)	At 90 DAS (%)	At harvest	
			Straw (%)	Grain (%)
T ₁ RDF (Control)	0.10	0.09	0.08	0.11
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	0.15	0.13	0.12	0.16
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	0.16	0.14	0.13	0.17
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	0.12	0.11	0.10	0.13
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	0.12	0.11	0.10	0.13
T ₆ RDF + Foliar application of ZnSO ₄ @	0.14	0.12	0.12	0.16

	0.5% at CRI, tillering and milking stage				
T ₇	RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	0.14	0.12	0.12	0.16
T ₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	0.11	0.10	0.09	0.12
T ₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	0.11	0.10	0.09	0.12
	SE (m)±	0.007	0.008	0.008	0.008
	CD at 5%	0.020	0.024	0.024	0.025

3.1.8 Sulphur Uptake

The data in Table 9 in respect of sulphur uptake by wheat grain, straw and total sulphur uptake by wheat were significantly influenced by various treatments.

The data indicated that significantly higher sulphur uptake by wheat grains (7.20 kg ha⁻¹) was observed with the treatment of RDF + ZnSO₄ @ 30 kg ha⁻¹ (T₃), which was statistically at par with RDF + ZnSO₄ @ 15 kg ha⁻¹ (T₂), RDF + foliar application of ZnSO₄ @ 1.0% at CRI, tillering, and milking stages (T₇), and RDF + foliar application of ZnSO₄ @ 0.5% at CRI, tillering, and milking stages (T₆). The lowest sulphur uptake in grains (3.96 kg ha⁻¹) was recorded in the recommended dose of fertilizer (RDF 80:40:40 NPK kg ha⁻¹) (T₁).

A similar trend was observed for sulphur uptake by wheat straw, with the highest uptake (8.27 kg ha⁻¹) in T₃, statistically at par with T₂, T₇, and T₆, and the lowest uptake (4.24 kg ha⁻¹) in T₁. The total sulphur uptake by wheat was also highest (15.46 kg ha⁻¹) in T₃, at par with T₂, T₇, and T₆, while the lowest total uptake (8.20 kg ha⁻¹) was recorded in T₁.

These findings align with the results reported by Kumar and Singh (1979), Ravi *et al.* (2008), Kumar *et al.* (2010), Patil (2012) and Saralet *et al.* (2024).

Table 9. Effect of different sources and levels of zinc on uptake of sulphur by wheat

Treatments	Sulphur uptake (kg ha ⁻¹)			
	Grain	Straw	Total	
T ₁ RDF (Control)	3.96	4.24	8.20	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	6.49	7.51	14.01	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	7.20	8.27	15.46	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	5.48	6.42	11.90	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	5.50	6.22	11.72	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	6.07	6.72	12.79	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	6.16	6.79	12.95	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	4.23	4.84	9.08	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	4.30	4.77	9.07	
	SE (m)±	0.51	0.57	0.91
	CD at 5%	1.53	1.71	2.74

3.1.9 Zinc Content

The data in respect of zinc content at different growth stages in wheat are presented in Table 10. Data indicated that zinc content in grain and straw at different growth stages was found to be significantly influenced by the application of various levels of zinc.

Zinc content in wheat straw at 60 DAS was significantly influenced by zinc application treatments. The highest zinc content (50.25 mg kg⁻¹) was recorded with RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃), statistically at par with RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T₅), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T₂), RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T₄), and RDF + foliar application of ZnSO₄ @ 1.0% at CRI, tillering, and milking stages (T₇), which had zinc contents of 49.76, 48.34, 46.81, and 45.48 mg kg⁻¹, respectively. The lowest zinc content (40.16 mg kg⁻¹) was observed with the recommended dose of fertilizer (RDF 80:40:40 NPK kg ha⁻¹) (T₁).

At 90 DAS, a decrease in zinc concentration was observed compared to 60 DAS, attributed to reduced metabolic activity and zinc absorption during this growth phase. The highest zinc content (48.68 mg kg⁻¹) was again recorded with T₃, followed by T₅ (47.71 mg kg⁻¹), T₂ (45.55 mg kg⁻¹), T₄ (44.03 mg kg⁻¹), and T₇ (42.75 mg kg⁻¹). All treatments except T₁ (38.80 mg kg⁻¹) were statistically at par.

At harvest, the highest zinc content in wheat straw (45.69 mg kg⁻¹) and grain (29.19 mg kg⁻¹) was recorded in T₃, followed by T₅ (43.90 and 28.95 mg kg⁻¹), T₂ (42.82 and 27.30 mg kg⁻¹), T₄ (41.58 and 26.86 mg kg⁻¹), and T₇ (41.34 and 26.09 mg kg⁻¹). The lowest zinc content in straw (37.59 mg kg⁻¹) and grain (23.42 mg kg⁻¹) was observed with T₁. All treatments, except T₁, were statistically similar.

The findings align with the reports of Kanwalet *et al.* (2010), Singh *et al.* (2014), Yadav *et al.* (2024), Prajapati *et al.* (2023) and Sardar *et al.* (2024), who observed a significant increase in zinc concentration in grain and straw with zinc application.

The results highlight the critical role of micronutrients in enhancing nutrient concentration, uptake, and utilization in crop production.

Table 10. Effect of different sources and levels of zinc on the content of zinc in wheat

Treatments	At 60 DAS (mg kg ⁻¹)	At 90 DAS (mg kg ⁻¹)	At harvest	
			Straw (mg kg ⁻¹)	Grain (mg kg ⁻¹)
T ₁ RDF (Control)	40.16	38.80	37.59	23.42
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	48.34	45.55	43.90	27.30
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	50.25	48.68	45.69	29.19
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	46.81	44.03	42.82	26.86
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	49.76	47.71	45.58	28.95
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	43.71	41.67	39.20	25.37
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	45.48	42.75	41.34	26.09
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	43.62	41.88	38.52	24.71
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	42.55	40.25	38.10	24.00
SE (m)±	2.12	2.06	1.95	1.25

CD at 5% 6.35 6.17 5.85 3.75

3.1.10 Zinc Uptake

The data pertaining to the uptake of zinc by wheat grain, straw and total uptake as influenced by various zinc treatments are presented in Table 11.

The data showed that zinc uptake by wheat grain and straw was significantly influenced by varying levels of zinc application, with all zinc treatments performing significantly better than the control.

The highest zinc uptake by grain (125.85 g ha⁻¹) was observed in the treatment of RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3), which was statistically at par with RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T5), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T2), and RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T4). The lowest uptake (84.21 g ha⁻¹) was recorded with the recommended dose of fertilizer (RDF 80:40:40 NPK kg ha⁻¹) (T1).

Similarly, the highest zinc uptake by straw (297.50 g ha⁻¹) was observed in T3, statistically at par with T5, T2, and T4. The lowest uptake (199.26 g ha⁻¹) was recorded in T1.

Total zinc uptake by wheat was also highest in T3 (423.35 g ha⁻¹), followed by T5, T2, and T4, all of which were statistically similar. The lowest total uptake (283.47 g ha⁻¹) was observed in T1.

The improved zinc uptake with zinc fertilization can be attributed to enhanced nutrient availability in the rhizosphere, leading to increased metabolic and photosynthetic activity, greater dry matter production, and higher total zinc uptake.

These findings align with the results reported by Kabeya and Shankar (2013), Keramet *et al.* (2014), Yadav *et al.* (2024), Prajapati *et al.* (2023) and Sardar *et al.* (2024).

Table 11. Effect of different sources and levels of zinc on uptake of zinc by wheat

Treatments	Zinc uptake (g ha ⁻¹)			
	Grain	Straw	Total	
T ₁ RDF (Control)	84.21	199.26	283.47	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	112.82	272.22	385.03	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	125.85	297.50	423.35	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	110.30	264.86	375.15	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	122.70	293.39	416.10	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	94.29	214.01	308.30	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	97.43	227.24	324.67	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	89.33	205.37	294.70	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	87.34	202.42	289.76	
	SE (m)±	6.71	15.71	18.49
	CD at 5%	20.11	47.10	55.44

3.1.11 Iron Content

The iron content of wheat at different growth stages of wheat is presented in Table 12.

The highest iron content in wheat straw at 60 DAS (268.31 mg kg⁻¹) was recorded in the treatment of RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3), followed by RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T5), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T2), and RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T4). The lowest iron content (264.20 mg kg⁻¹) was observed in the recommended dose of fertilizer (RDF 80:40:40 NPK kg ha⁻¹, T1). The increase in iron

content with zinc application may be attributed to enhanced metabolic activity. However, the differences in treatments were not statistically significant.

At 90 DAS, iron content in straw decreased compared to 60 DAS. The maximum iron content (253.64 mg kg⁻¹) was recorded in T3, while the lowest (248.94 mg kg⁻¹) was observed in T1. A similar trend of increased iron content with zinc application was noted, though the differences among treatments remained non-significant.

At harvest, the highest iron content in grain and straw (258.00 and 229.20 mg kg⁻¹, respectively) was recorded in T3. The lowest content (236.62 and 194.64 mg kg⁻¹ in grain and straw, respectively) was observed in T1. The increase in iron content with zinc application could be due to enhanced absorption of iron during plant growth. As with earlier stages, the differences in treatments were statistically non-significant.

These findings align with results reported by Chavan (2015) and Sardar *et al.* (2024) who observed the highest iron content in chickpea under soil application of ZnSO₄ @ 30 kg ha⁻¹.

Table 12. Effect of different sources and levels of zinc on the content of iron in wheat

Treatments	At 60 DAS (mg kg ⁻¹)	At 90 DAS (mg kg ⁻¹)	At harvest	
			Straw (mg kg ⁻¹)	Grain (mg kg ⁻¹)
T ₁ RDF (Control)	264.20	248.94	236.62	194.64
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	266.25	251.80	252.57	228.39
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	268.31	253.64	258.00	229.20
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	265.96	251.52	251.50	221.97
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	267.59	252.76	254.81	222.81
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	265.19	250.63	241.75	198.22
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	265.55	251.01	263.38	201.23
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	265.11	249.84	239.26	197.84
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	264.72	249.20	237.95	196.72
SE (m)±	12.43	11.95	11.70	10.68
CD at 5%	NS	NS	NS	NS

3.1.12 Iron uptake

The data pertaining to the uptake of iron by wheat grain, straw and total uptake as influenced by various zinc treatments are presented in Table 13.

The data showed that iron uptake by wheat grain and straw was significantly influenced by various zinc treatments. The uptake of iron was statistically higher under zinc-treated conditions compared to the control.

The highest iron uptake by grain (989.32 g ha⁻¹) was observed with RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3). This was statistically at par with RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T5), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T2), and RDF + Zn

EDTA @ 1.5 kg ha⁻¹ (T4). The lowest uptake (700.47 g ha⁻¹) was recorded in the recommended dose of fertilizer (RDF 80:40:40 NPK kg ha⁻¹, T1).

Similarly, the highest iron uptake by straw (1684.60 g ha⁻¹) was also noted in T3, which was statistically comparable to T5, T2, and T4. The lowest uptake (1230.05 g ha⁻¹) was recorded in T1.

The total iron uptake by wheat was highest (2673.92 g ha⁻¹) in T3, followed by T5, T2, and T4, all of which were statistically at par. The lowest total uptake (1930.52 g ha⁻¹) was observed in T1.

These findings align with earlier studies, such as Anonymous (1984) and Sardar *et al.* (2024) which also reported a positive interactive effect of zinc on iron uptake.

Table 13. Effect of different sources and levels of zinc on the uptake of iron by wheat

Treatments	Iron uptake (g ha ⁻¹)		
	Grain	Straw	Total
T ₁ RDF (Control)	700.47	1230.05	1930.52
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	948.41	1579.31	2527.71
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	989.32	1684.60	2673.92
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	911.21	1558.27	2469.48
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	943.49	1636.06	2579.54
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	733.64	1317.51	2051.14
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	758.50	1463.74	2222.23
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	715.71	1283.95	1999.65
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	707.14	1265.29	1972.43
SE (m)±	58.14	99.68	137.59
CD at 5%	174.32	298.84	412.51

3.1.13 Copper Content

The copper content of wheat at different growth stages was presented in Table 14.

The data indicated that copper content in straw samples at 60 and 90 DAS across different treatments did not differ significantly, as the single application of RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3) was completed at this stage. However, copper content decreased from 60 to 90 DAS. The highest copper content at 60 DAS (16.98 mg kg⁻¹) was observed in T3, while the lowest (15.24 mg kg⁻¹) was recorded in RDF 80:40:40 NPK kg ha⁻¹ (T1).

At 90 DAS, T3 again exhibited the highest copper content (15.63 mg kg⁻¹), and the lowest content (14.17 mg kg⁻¹) was observed in T1.

At harvest, copper content in grain was significantly different among treatments, while the straw content showed no significant difference. The highest copper content in straw and grain (15.30 mg kg⁻¹ and 8.84 mg kg⁻¹, respectively) was recorded in T3. In contrast, the lowest values (13.16 mg kg⁻¹ in straw and 7.45 mg kg⁻¹ in grain) were observed in T1. Overall, copper content in straw was higher compared to grains.

An increase in copper content with higher zinc application was noted, aligning with findings by Ping *et al.* (2008), Mollahet *et al.* (2009) and Sardar *et al.* (2024) in rice crops.

Table 14. Effect of different sources and levels of zinc on the content of copper in wheat

Treatments	At 60	At 90	At harvest
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		DAS (mg kg ⁻¹)	DAS (mg kg ⁻¹)	Straw (mg kg ⁻¹)	Grain (mg kg ⁻¹)
T ₁	RDF (Control)	15.24	14.17	13.16	7.45
T ₂	RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	16.60	15.50	15.10	8.69
T ₃	RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	16.98	15.63	15.30	8.84
T ₄	RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	16.58	15.44	14.89	8.45
T ₅	RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	16.73	15.55	15.85	8.72
T ₆	RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	15.82	14.72	13.23	7.48
T ₇	RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	15.99	14.83	13.44	7.67
T ₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	15.71	14.66	13.21	7.47
T ₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	15.70	14.52	13.20	7.46
	SE (m)±	0.75	0.73	0.69	0.38
	CD at 5%	NS	NS	NS	1.15

3.1.14 Copper Uptake

The data pertaining to the copper uptake in grain, straw and total uptake by wheat was presented in Table 15.

The results were found to be significant with the application of zinc with different treatments.

The uptake of copper by wheat grain and straw was significantly influenced by various zinc treatments. The highest copper uptake by grain (38.13 g ha⁻¹) was recorded in the treatment RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T3), which was statistically at par with treatments RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T5), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T2), and RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T4). The lowest uptake (26.98 g ha⁻¹) was observed in the recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T1).

Similarly, the highest copper uptake by straw (99.79 g ha⁻¹) was also recorded in T3, statistically at par with T5, T2, and T4. The lowest uptake (69.36 g ha⁻¹) was noted in T1.

The total copper uptake was maximized (137.92 g ha⁻¹) in T3, with statistically similar results observed in T5, T2, and T4. The lowest total uptake (96.34 g ha⁻¹) was recorded in T1.

These findings align with the results reported by Kadam (2017) and Sardar *et al.* (2024), confirming the positive influence of zinc application on copper uptake in wheat.

Table 15. Effect of different sources and levels of zinc on the uptake of copper by wheat

Treatments	Copper uptake (g ha ⁻¹)		
	Grain	Straw	Total
T ₁ RDF (Control)	26.98	69.36	96.34
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	35.68	94.93	130.62

T ₃	RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	38.13	99.79	137.92
T ₄	RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	34.55	92.21	126.76
T ₅	RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	37.25	101.89	139.14
T ₆	RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	27.92	71.89	99.82
T ₇	RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	28.37	75.43	103.80
T ₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	26.95	70.65	97.60
T ₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	27.56	70.00	97.56
	SE (m)±	2.11	6.96	7.92
	CD at 5%	6.33	20.86	23.73

3.1.15 Manganese Content

Data pertaining to the manganese content of wheat at different growth stages were presented in Table 16.

At 60 DAS, the highest manganese content in wheat straw (201.95 mg kg⁻¹) was observed in the treatment RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃), while the lowest manganese content (198.77 mg kg⁻¹) was recorded in the treatment RDF 80:40:40 NPK kg ha⁻¹ (T₁).

At 90 DAS, a similar trend was observed, with the highest manganese content (185.94 mg kg⁻¹) in T₃ and the lowest (183.13 mg kg⁻¹) in T₁.

At harvest, the maximum manganese content in straw (181.50 mg kg⁻¹) and grain (71.88 mg kg⁻¹) was recorded in T₃. This was followed by the treatment RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T₅), which recorded manganese content of 177.40 mg kg⁻¹ in straw and 69.16 mg kg⁻¹ in grain. The lowest manganese content in straw (162.90 mg kg⁻¹) and grain (54.98 mg kg⁻¹) was observed in T₁.

Manganese content in grain was significantly affected by treatments, while in straw, T₁, T₈, and T₉ were statistically at par. Results showed that the application of zinc positively influenced manganese content in wheat, exhibiting a linear trend.

These findings align with those of Kumar *et al.* (2017), who noted that the application of 10 kg ha⁻¹ of zinc maximized the content of N, P, K, Zn, Fe, and Mn in grain and straw. The synergistic effect of zinc on manganese content in plants was also reported by Meena *et al.* (2017) and Sardar *et al.* (2024).

Table 16. Effect of different sources and levels of zinc on the content of manganese in wheat

Treatments	At 60 DAS (mg kg ⁻¹)	At 90 DAS (mg kg ⁻¹)	At harvest	
			Straw (mg kg ⁻¹)	Grain (mg kg ⁻¹)
T ₁ RDF (Control)	198.77	183.13	162.90	54.98
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	201.87	185.31	179.23	68.71
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	201.95	185.94	181.50	71.88
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	201.83	184.70	176.94	67.16
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	201.89	184.78	177.40	69.16
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	199.90	184.50	166.94	64.07

T ₇	RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	199.81	184.81	174.82	65.87
T ₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	199.51	183.98	165.56	62.41
T ₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	199.01	183.90	164.87	61.63
	SE (m)±	9.16	9.92	8.47	3.03
	CD at 5%	NS	NS	NS	9.09

3.1.16 Manganese Uptake

The data pertaining to the manganese uptake by grain, straw and total uptake by wheat is presented in Table 17. The manganese uptake was observed significant with the application of zinc.

The highest manganese uptake by wheat grain (310.85 g ha⁻¹) was observed in the treatment RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃), which was statistically at par with treatments such as RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T₅), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T₂), and RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T₄). The lowest manganese uptake in grain (197.40 g ha⁻¹) was recorded in the recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁).

In wheat straw, the highest manganese uptake (1184.95 g ha⁻¹) was also observed in T₃, statistically at par with T₅, T₂, and T₄. The lowest uptake in straw (840.13 g ha⁻¹) was recorded in T₁.

The total manganese uptake by wheat was highest (1495.80 g ha⁻¹) in T₃, which was statistically comparable with T₅, T₂, and T₄. The lowest total uptake (1037.53 g ha⁻¹) was observed in T₁.

These results are consistent with the findings of Kadam (2017) and Sardar *et al.* (2024).

Table 17. Effect of different sources and levels of zinc on uptake of manganese by wheat

Treatments	Manganese uptake (g ha ⁻¹)			
	Grain	Straw	Total	
T ₁ RDF (Control)	197.40	840.13	1037.53	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	285.28	1117.89	1403.17	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	310.85	1184.95	1495.80	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	276.03	1096.05	1372.08	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	292.31	1140.50	1432.82	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	237.58	908.71	1146.30	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	247.02	972.70	1219.71	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	225.98	885.93	1111.91	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	222.49	875.89	1098.38	
	SE (m)±	18.34	60.64	75.15
	CD at 5%	55.00	181.81	225.29

3.2 Effect of different sources and levels of zinc on soil fertility status after the harvest of wheat

The effect of different sources and levels of zinc on some of the chemical properties of soil under wheat crops was recorded and discussed.

3.2.1 Soil pH (1:2.5)

Soil pH is an intrinsic property that is decided by the exchangeable cations on the clay surface and takes a larger time to get changed. The data presented in Table 18 indicated that the pH of the soil ranged from (8.12 to 8.19) indicating that the soil was slightly alkaline in reaction. The higher value of pH (8.19) was recorded in the treatment recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁). The lowest pH (8.12) was recorded with the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). This indicates that the application of zinc reduced the soil pH. However, treatment-wise variation in pH was found to be non-significant. Keramet *al.* (2014), Rakshithaet *al.* (2023) and Jajraet *al.* (2022).

3.2.2 EC (dS m⁻¹)

Electrical conductivity is a measure of soluble salt concentration in soil. A higher amount of salt in soil restricts nutrient uptake and thus affects plant growth. The data concerning electrical conductivity ranged from 0.24 to 0.29 dS m⁻¹. However, the data indicated that a lower value (0.24 dS m⁻¹) was found in the treatment of RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). The higher value (0.29 dS m⁻¹) of electrical conductivity was recorded in the treatment of RDF (T₁). However, treatment-wise variation in EC was found to be non-significant. Keramet *al.* (2014), Rakshithaet *al.* (2023) and Jajraet *al.* (2022).

3.2.3 Organic carbon

Organic carbon is an indication of the organic carbon fraction of soil formed due to microbial decomposition of organic residue.

The data in Table 18 pertaining to the organic carbon of soil as influenced by different treatments ranged from 0.47 to 0.50 per cent. However, treatment-wise variation in organic carbon was found to be non-significant. This indicates that the highest (0.50%) organic carbon was recorded with the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃) and the lowest value (0.47%) of organic carbon was found in the treatment of recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁), RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage (T₈) and RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage (T₉). Keramet *al.* (2014), Rakshithaet *al.* (2023) and Jajraet *al.* (2022).

3.2.4 Calcium carbonate

The data in Table 18 pertaining to the calcium carbonate of soil as influenced by different treatments were non-significant and they ranged from 5.42 to 6.00 per cent, indicating that the highest (6.00%) calcium carbonate was recorded with the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). The lower value (5.42% of calcium carbonate was found in the treatment of recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁). Keramet *al.* (2014).

Table 18. Effect of different sources and levels of zinc on chemical properties of soil

Treatments	pH (1:2.5)	EC (dS m ⁻¹)	OC (%)	CaCO ₃ (%)
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T ₁	RDF (Control)	8.19	0.29	0.47	5.42
T ₂	RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	8.14	0.26	0.49	5.67
T ₃	RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	8.12	0.24	0.50	6.00
T ₄	RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	8.15	0.27	0.48	5.75
T ₅	RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	8.13	0.25	0.49	5.75
T ₆	RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	8.17	0.26	0.48	5.50
T ₇	RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	8.16	0.25	0.48	5.58
T ₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	8.17	0.28	0.47	5.50
T ₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	8.18	0.28	0.47	5.58
	SE (m)±	0.39	0.013	0.023	0.31
	CD at 5%	NS	NS	NS	NS

3.3 Effect of different sources and levels of zinc on available macronutrients in the soil

The data pertaining to the available macronutrient content in the soil after harvest is presented in Table 19.

3.3.1 Available nitrogen status

The result pertaining to available nitrogen status in Table 19 was not significantly influenced by different treatments. The available nitrogen in the soil varied from 196.52 to 217.43 kg ha⁻¹ indicating that the soil was low in available nitrogen content.

The highest available nitrogen (217.43 kg ha⁻¹) was observed with the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). The soil application of zinc increased the available nitrogen more than the RDF treatment. The lower value (196.52 kg ha⁻¹) of available nitrogen was found in the treatment of recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁).

This result may be due to the beneficial effect of zinc in improving soil properties and enhancing the availability in soil has been reported by Latha *et al.* (2001), and Singh *et al.* (2007) also reported that increases in available nitrogen with the application of zinc. The beneficial role of zinc in the increase in the CEC of roots helped in the increased absorption of nutrients from the soil. Further, the zinc in chlorophyll formation, regulation of the auxin concentration and stimulatory effect on most of the physiological and metabolic processes of the plant might help the plant in enhanced absorption of nutrients from soil these results are in accordance with the finding of Dwivedi *et al.* (2002), Prajapati *et al.* (2023) and Rakshitha *et al.* (2023).

Chavan (2015) reported the highest increase in available nitrogen in chickpeas was noted in the soil application of ZnSO₄ @ 30 kg ha⁻¹ and was 6.1% higher than the control treatment.

3.3.2 Available phosphorous status

It is evident from the data in Table 19 that the available phosphorous content of the soil varied significantly, and it ranged from 11.98 to 15.64 kg ha⁻¹ indicating that the soil was medium in available phosphorous content.

The highest value of available phosphorous (15.65 kg ha⁻¹) was observed in the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). The soil application of zinc increased the

available phosphorous more than the RDF treatment. The lower value (11.98 kg ha⁻¹) of available phosphorous was observed in the recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁).

This result was in agreement with the results of Singh *et al.* (2007), Singh *et al.* (2014), Prajapati *et al.* (2023) and Rakshitha *et al.* (2023). They reported that available phosphorous content was seemingly increased with the application of zinc.

3.3.3 Available potassium status

The data in Table 19 on the available potassium content of the soil is significant which ranged from 301.06 to 336.52 kg ha⁻¹ indicating that the soil was very high in available potassium content. The highest potassium (336.52 kg ha⁻¹) was observed with the treatment of RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃). The lower value (301.06 kg ha⁻¹) of available potassium was observed in the recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁).

Chavan (2015) reported that increasing the dose of zinc sulphate from 10 to 30 kg ha⁻¹ indicated an increase in available potassium linearly. This result was supported by Singh *et al.* (2014). That increase in available potassium in soil with the increase in the application was recorded by Singh *et al.* (2007), Varma and Mathur (2009) and Rakshitha *et al.* (2023).

3.3.4 Available Sulphur status

The data on the available sulphur content of the soil in Table 19 varied significantly from 11.72 to 15.09 mg kg⁻¹ indicating that the soil was medium in available sulphur content.

The highest available sulphur (15.09 mg kg⁻¹) was observed with the RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃) and it was significantly higher than other treatments. The treatment which shows lower available sulphur content than RDF + Zn EDTA @ 3.0 kg ha⁻¹ (T₅), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T₂), RDF + Zn EDTA @ 1.5 kg ha⁻¹ (T₄) and RDF + Foliar application of ZnSO₄ @ 1.0% at CRI, tillering and milking stage (T₇) which contains available sulphur content as 13.80, 13.72, 13.42 and 13.38 mg kg⁻¹ respectively. The lowest amount (11.72 mg kg⁻¹) of available sulphur was observed in the treatment recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁).

These results were in agreement with Singh *et al.* (2014), Chavan (2015) and Rakshitha *et al.* (2023). Sulphur content in zinc sulphate might be the reason for the increase in the available sulphur content in the soil.

Table 19. Effect of different sources and levels of zinc on available nutrients in the soil

Treatments	Available macronutrients			
	N	P	K	S
	(kg ha ⁻¹)			(mg kg ⁻¹)
T ₁ RDF (Control)	196.52	11.98	301.06	11.72
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	209.07	14.62	331.63	13.72
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	217.43	15.64	336.52	15.09
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	209.07	13.81	322.00	13.42
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	213.25	14.83	332.42	13.80
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	204.89	13.51	314.38	12.73
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	204.89	13.61	317.86	13.38

T ₈	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	200.70	13.20	310.76	12.85
T ₉	RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	200.70	12.08	307.22	12.12
	SE (m)±	6.39	0.68	7.44	0.62
	CD at 5%	NS	2.02	22.32	1.86

3.4 Effect of different sources and levels of zinc on available micronutrients status in the soil

The data in respect of the available micronutrient status of soil at the harvest of wheat are presented in Table 20.

3.4.1 Available zinc status

The data in respect of the effect of different sources and levels of zinc on available zinc status was found to be significant. The highest available zinc (0.55 mg kg^{-1}) was observed with the treatment of RDF + soil application of $\text{ZnSO}_4 @ 30 \text{ kg ha}^{-1}$ (T₃) and it was statistically superior over other treatments. The lowest available zinc (0.45 mg kg^{-1}) was recorded in the treatment of recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha^{-1} (T₁). The soil application of RDF + $\text{ZnSO}_4 @ 30 \text{ kg ha}^{-1}$ (T₃) increased available zinc over (T₁) while this treatment also showed an increase in available zinc over the RDF + Zn EDTA @ 3.0 kg ha^{-1} (T₅), RDF + soil application of $\text{ZnSO}_4 @ 15 \text{ kg ha}^{-1}$ (T₂) and RDF + Zn EDTA @ 1.5 kg ha^{-1} (T₄) is the 0.54, 0.51, 0.49 and mg kg^{-1} respectively. The lowest available zinc (0.45 mg kg^{-1}) was observed in the treatment recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha^{-1} (T₁). These results were in agreement with Chavan (2015). A similar result was observed by Prasad *et al.* (2010), Rathod *et al.* (2012), Prajapati *et al.* (2023) and Rakshitha *et al.* (2023).

3.4.2 Available iron status

The effect of different sources and levels of zinc on available iron was found to be non-significant. The highest available iron (5.19 mg kg^{-1}) was observed with RDF + soil application of $\text{ZnSO}_4 @ 30 \text{ kg ha}^{-1}$ (T₃). But it was followed by treatment such as RDF + soil application of Zn EDTA @ 3.0 kg ha^{-1} (T₅) and RDF + soil application of $\text{ZnSO}_4 @ 15 \text{ kg ha}^{-1}$ (T₂) which is available iron (5.18 mg kg^{-1}) and lowest available iron (5.15 mg kg^{-1}) was recorded in treatment recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha^{-1} (T₁). (Rakshitha *et al.*, 2023).

3.4.3 Available copper status

The effect of different sources and levels of zinc on available copper was found to be non-significant. The highest available copper (3.45 mg kg^{-1}) was observed with RDF + soil application of $\text{ZnSO}_4 @ 30 \text{ kg ha}^{-1}$ (T₃). But it was followed by treatments such as RDF + Zn EDTA @ 3.0 kg ha^{-1} (T₅), RDF + soil application of $\text{ZnSO}_4 @ 15 \text{ kg ha}^{-1}$ (T₂) and RDF + Zn EDTA @ 1.5 kg ha^{-1} (T₄) in which available copper is (3.44 mg kg^{-1}) and lowest available copper (3.40 mg kg^{-1}) was recorded in treatment recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha^{-1} (T₁). (Rakshitha *et al.*, 2023).

3.4.4 Available manganese status

The effect of different sources and levels of zinc on available manganese was found to be non-significant. The highest available manganese (4.59 mg kg^{-1}) was observed with RDF + soil application of $\text{ZnSO}_4 @ 30 \text{ kg ha}^{-1}$ (T₃). But it was followed by treatments such as RDF + Zn EDTA @ 3.0 kg ha^{-1} (T₅), RDF + soil application of $\text{ZnSO}_4 @ 15 \text{ kg ha}^{-1}$ (T₂) and RDF + Zn EDTA @ 1.5 kg ha^{-1} (T₄) in which available manganese is (4.58

mg kg⁻¹) and lowest available manganese (4.54 mg kg⁻¹) was recorded in treatment recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁). (Rakshitha *et al.*, 2023).

Table 20. Effect of different sources and levels of zinc on available micronutrients in the soil

Treatments	Available micronutrients				
	Zn	Fe	Cu	Mn	
	(mg kg ⁻¹)				
T ₁ RDF (Control)	0.45	5.15	3.40	4.54	
T ₂ RDF + Soil application of ZnSO ₄ @ 15 kg ha ⁻¹	0.51	5.18	3.44	4.58	
T ₃ RDF + Soil application of ZnSO ₄ @ 30 kg ha ⁻¹	0.55	5.19	3.45	4.59	
T ₄ RDF + Soil application of Zn EDTA @ 1.5 kg ha ⁻¹	0.49	5.17	3.44	4.58	
T ₅ RDF + Soil application of Zn EDTA @ 3.0 kg ha ⁻¹	0.54	5.18	3.44	4.58	
T ₆ RDF + Foliar application of ZnSO ₄ @ 0.5% at CRI, tillering and milking stage	0.47	5.16	3.42	4.56	
T ₇ RDF + Foliar application of ZnSO ₄ @ 1.0% at CRI, tillering and milking stage	0.48	5.17	3.42	4.57	
T ₈ RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage	0.46	5.16	3.41	4.56	
T ₉ RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage	0.46	5.16	3.42	4.56	
	SE (m)±	0.023	0.24	0.16	0.21
	CD at 5%	0.068	NS	NS	NS

4. CONCLUSION

From the present investigation, it is concluded that the soil application of ZnSO₄ @ 30 kg ha⁻¹ along with a recommended dose of fertilizer significantly influenced the nutrient content and N, P, K, S, Zn, Fe, Cu, and Mn uptake of wheat. Also, concluded that soil application was better than a foliar application of zinc.

The highest N, P, K, S, Zn, Fe, Cu and Mn content and uptake were observed with RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃), followed by treatment of RDF + soil application of Zn EDTA @ 3.0 kg ha⁻¹ (T₅), RDF + soil application of ZnSO₄ @ 15 kg ha⁻¹ (T₂) and RDF + Soil application of Zn EDTA @ 1.5 kg ha⁻¹ (T₄). The lowest nutrient content and uptake were observed in (RDF) 80:40:40 NPK kg ha⁻¹ (T₁) treatment.

The effect of different levels of zinc registered a non-significant effect on soil pH, EC, Organic Carbon, Calcium Carbonate, Available Nitrogen, Iron, Manganese and Copper content, however significant effect on Available Phosphorous, Potassium, Sulphur and Zinc content was observed.

Soil available P, K, S and Zn were highest in RDF + soil application of ZnSO₄ @ 30 kg ha⁻¹ (T₃) and the lowest soil available P, K, S and Zn were observed by the recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha⁻¹ (T₁) treatment.

Therefore, it is concluded that the soil application of ZnSO₄ @ 30 kg ha⁻¹ along with a recommended dose of fertilizer recorded significant increases in nutrient content and N, P, K, S, Zn, Fe, Cu, and Mn uptake in wheat with improvement in soil fertility.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors declare that No AI technologies have been used during writing or editing this manuscript.

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