Original Research Article

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

ABSTRACT:

Indian farmers face challenges in wheat production due to poor soil nutrients and imbalanced fertilizer use, making zinc-supplemented fertilizers vital for boosting productivity. Wheat (*Triticum aestivum L.*) is a vital global food crop, rich in carbohydrates, protein, and essential nutrients, with India being a major producer, although many regions face significant zinc deficiency in their soils. A field study 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 $ZnSO_4$ @ 30 kg ha^{-1}.

It is concluded that the soil application of $ZnSO_4$ @ 30 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: Zinc, 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 percent of the total food grain production of the country. Wheat is called “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 percent 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 ‘thiamin’. Wheat proteins are of special significance. Wheat provides 'gluten' that creates the 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.

Katkar *et al.* (2013) experimented and gave district-wise deficiency of micronutrients in Vidarbha. In all, 498 soil samples were collected from 83 villages in 7 tehsils from the Akola districts, where Akola shows 70.5% Zn deficiency.

The combined use of NPK fertilizers is crucial for wheat production, timely and balanced application of NPK significantly impacts yield. Nitrogen, essential for growth, plays a key role in chlorophyll, proteins, and nucleic acids, while phosphorus supports seed formation, and its deficiency directly affects grain weight. Potassium enhances biochemical processes, improving drought tolerance and resistance to pests. Increased cropping intensity and high-yielding varieties have led to nutrient depletion in soils, making balanced NPK application vital. Additionally, sulfur (S), a secondary macronutrient, is essential for metabolic processes, protein production, photosynthesis, and nitrogen fixation, and directly contributes to wheat's baking quality. Deficiency of micronutrients (B, Cu, Fe, Mn, Mo, Ni, Zn, Cl) can severely impact plant growth and reduce yield. Despite wheat productivity, improper or insufficient use of micronutrient fertilizers exacerbates disease and pest problems, affecting its production. This study aims to determine the quantitative response of wheat to balanced NPK and micronutrient applications under semi-arid irrigated conditions.

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).

The experiment was laid out in Randomized Block Design (RBD) with nine treatments replicated three times as shown below in treatment details.

Plant nutrient content was determined by washing samples with tap and distilled water, followed by drying in the shade and then in a hot air oven at 64°C to a constant weight.

The dried samples were ground with an electric grinder, labeled accordingly, and stored in sample collection bags and used for nutrient analysis.

The nutrient uptake i.e., uptake of N, P, K, and S was calculated by considering grain and dry matter yield at harvest in the particular plot in relation to the concentration of the particular nutrient in the respective plot using the formula.

Uptake (kg ha-1)=Nutrient content (%) x Grain or straw yield (kg ha^{-1}) / 100

The nutrient uptake i.e., uptake of Zn, Fe, Cu and Mn was calculated by using the formula.

Uptake (g ha-1) =Nutrient content (%) x Grain or straw yield (kg ha^{-1}) / 1000

Soil samples were collected at 0-20 cm depthfrom each treatment plot after harvesting of wheat. Samples were air-dried in the 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 analysis of other parameters.

List 1- Treatment details:

T_1	The recommended dose of fertilizer (RDF) is 80:40:40 NPK kg ha^{-1}
T_2	RDF + Soil application of $ZnSO_4$ @ 15 kg ha^{-1}
T_3	RDF + Soil application of $ZnSO_4$ @ 30 kg ha^{-1}
T_4	RDF + Soil application of Zn EDTA @ 1.5 kg ha^{-1}
T_5	RDF + Soil application of Zn EDTA @ 3.0 kg ha^{-1}
T_6	RDF + Foliar application of $ZnSO_4$ @ 0.5% at CRI, tillering and milking stage
T_7	RDF + Foliar application of $ZnSO_4$ @ 1.0% at CRI, tillering and milking stage
T_8	RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage
T_9	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 Sulfur (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 $ZnSO_4$ @ 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 + ZnSO$_4$ @ 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 ZnSO$_4$ @ 15 kg ha^{-1} (T2), RDF + soil application of Zn EDTA @ 1.5 kg ha^{-1} (T4), and RDF + foliar application of ZnSO$_4$ @ 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), Keram *et al.* (2012), Keram *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 is 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 $ZnSO_4$ @ 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 Alam *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 is 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 $ZnSO_4$ @ 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), Keram *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 $ZnSO_4$ @ 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 + $ZnSO_4$ @ 15 kg ha^{-1} (T2), RDF + Zn EDTA @ 1.5 kg ha^{-1} (T4), and RDF + foliar application of $ZnSO_4$ @ 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 Ghasal *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 $ZnSO_4$ @ 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 $ZnSO_4$ @ 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), Keram *et al.* (2012), Keram *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 Sulfur Content

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

The sulfur content in wheat straw at the 60 DAS stage was highest (0.16%) in the treatment of RDF + soil application of $ZnSO_4$ @ 30 kg ha^{-1} (T3). This was statistically at par with treatments such as RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1} (T2), RDF + foliar application of $ZnSO_4$ @ 1.0% at CRI, tillering, and milking stage (T7), and RDF + foliar application of $ZnSO_4$ @ 0.5% at CRI, tillering, and milking stage (T6). The lowest sulfur content (0.10%) was observed in the RDF 80:40:40 NPK kg ha^{-1} (T1) treatment.

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

At the harvest stage, sulfur content in wheat straw decreased compared to the content at 90 DAS, due to a reduction in dry matter at harvest. The highest sulfur content (0.13%)

at harvest was observed in T3, which was statistically at par with T2, T7, and T6. The lowest sulfur content (0.08%) was recorded in T1.

At harvest, sulfur 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 sulfur 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 Saral *et al.* (2024).

Table 8. Effect of different sources and levels of zinc on the content of sulfur 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$_4$ @ 0.5% at CRI, tillering and milking stage	0.14	0.12	0.12	0.16
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 Sulfur Uptake

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

The data indicated that significantly higher sulfur uptake by wheat grains (7.20 kg ha^{-1}) was observed with the treatment of RDF + ZnSO$_4$ @ 30 kg ha^{-1} (T3), which was statistically at par with RDF + ZnSO$_4$ @ 15 kg ha^{-1} (T2), RDF + foliar application of ZnSO$_4$ @ 1.0% at CRI, tillering, and milking stages (T7), and RDF + foliar application of ZnSO$_4$ @ 0.5% at CRI, tillering, and milking stages (T6). The lowest sulfur 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 sulfur 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 sulfur 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 Saral *et al.* (2024).

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

Treatments		Sulfur 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 is 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 $ZnSO_4$ @ 30 kg ha^{-1} (T3), statistically at par with RDF + Zn EDTA @ 3.0 kg ha^{-1} (T5), RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1} (T2), RDF + Zn EDTA @ 1.5 kg ha^{-1} (T4), and RDF + foliar application of $ZnSO_4$ @ 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 Kanwal *et al.* (2010), Singh *et al.* (2014), Prajapati *et al.* (2023), Sardar *et al.* (2024), and Yadav *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 is 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 $ZnSO_4$ @ 30 kg ha^{-1} (T3), which was statistically at par with RDF + Zn EDTA @ 3.0 kg ha^{-1} (T5), RDF + soil application of $ZnSO_4$ @ 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 Keram *et al.* (2012),Kabeya and Shankar (2013), Keram *et al.* (2014), Prajapati *et al.* (2023), Sardar *et al.* (2024), and Yadav *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 ZnSO$_4$ @ 30 kg ha^{-1} (T3), followed by RDF + Zn EDTA @ 3.0 kg ha^{-1} (T5), RDF + soil application of ZnSO$_4$ @ 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 ZnSO$_4$ @ 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	265.55	251.01	263.38	201.23

	$ZnSO_4$ @ 1.0% at CRI, tillering and milking stage				
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 is 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 $ZnSO_4$ @ 30 kg ha^{-1} (T3). This was statistically at par with RDF + Zn EDTA @ 3.0 kg ha^{-1} (T5), RDF + soil application of $ZnSO_4$ @ 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 is 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 $ZnSO_4$ @ 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), Mollah *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 DAS (mg kg^{-1})	At 90 DAS (mg kg^{-1})	At harvest	
				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 is 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 $ZnSO_4$ @ 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 $ZnSO_4$ @ 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 is 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 $ZnSO_4$ @ 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 $ZnSO_4$ @ 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 $ZnSO_4$ @ 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 statusafter the harvest of wheat

The effect of different sources and levels of zinc on some of the chemical properties of soil underwheat 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} (T_1). The lowest pH (8.12) was recorded with the RDF + soil application of $ZnSO_4$ @ 30 kg ha^{-1} (T_3). This indicates that the application of zinc reduced the soil pH. However, treatment-wise variation in pH was found too non-significant. Keram *et al.* (2014), Jajra*et al*. (2022), and Rakshitha *et al*. (2023).

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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3). The higher value (0.29 dS m^{-1}) of electrical conductivity was recorded in the treatment of RDF (T_1). However, treatment-wise variation in EC was found to be non-significant. Keram *et al.* (2014),Jajra*et al*. (2022), and Rakshitha *et al.* (2023),

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 percent. 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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3) 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} (T_1), RDF + Foliar application of Zn EDTA @ 0.25% at CRI, tillering and milking stage (T_8) and RDF + Foliar application of Zn EDTA @ 0.5% at CRI, tillering and milking stage (T_9). Keram *et al.* (2014), Jajra*et al*. (2022), and Rakshitha *et al.* (2023).

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 percent, indicating that the highest (6.00%) calcium carbonate was recorded with the RDF + soil application of $ZnSO_4$ @ 30 kg ha^{-1} (T_3). 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} (T_1). Keram *et al.* (2014).

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

Treatments		pH (1:2.5)	EC (dS m^{-1})	OC (%)	$CaCO_3$ (%)
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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3). 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} (T_1).

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), andRakshitha *et al.* (2023).

Chavan (2015), reported the highest increase in available nitrogen in chickpeas was noted in the soil application of $ZnSO_4$ @ 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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3) 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} (T_1).

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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3). 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} (T_1).

Chavan (2015), reported that increasing the dose of zinc sulfate 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 Sulfur status

The data on the available sulfur 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 sulfur content.

The highest available sulfur (15.09 mg kg^{-1}) was observed with the RDF + soil application of $ZnSO_4$ @ 30 kg ha^{-1} (T_3) and it was significantly higher than other treatments. The treatment which shows lower available sulfur content than RDF + Zn EDTA @ 3.0 kg ha^{-1} (T_5), RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1} (T_2), RDF + Zn EDTA @ 1.5 kg ha^{-1} (T_4) and RDF + Foliar application of $ZnSO_4$ @ 1.0% at CRI, tillering and milking stage (T_7) which contains available sulfur 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 sulfur was observed in the treatment recommended dose of fertilizer (RDF) 80:40:40 NPK kg ha^{-1} (T_1).

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

Table 19. Effect of different sources and levels of zinc on available nutrientsin 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 is 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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3) 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} (T_1). The soil application of RDF + $ZnSO_4$ @ 30 kg ha^{-1} (T_3) increased available zinc over (T_1) while this treatment also showed an increase in available zinc over the RDF + Zn EDTA @ 3.0 kg ha^{-1} (T_5), RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1} (T_2) and RDF + Zn EDTA @ 1.5 kg ha^{-1} (T_4) 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} (T_1). 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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3). But it was followed by treatment such as RDF +

soil application of Zn EDTA @ 3.0 kg ha^{-1} (T_5) and RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1} (T_2) 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} (T_1). (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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3). But it was followed by treatments such as RDF + Zn EDTA @ 3.0 kg ha^{-1} (T_5), RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1} (T_2) and RDF + Zn EDTA @ 1.5 kg ha^{-1} (T_4) 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} (T_1). (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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3). But it was followed by treatments such as RDF + Zn EDTA @ 3.0 kg ha^{-1} (T_5), RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1} (T_2) and RDF + Zn EDTA @ 1.5 kg ha^{-1} (T_4) 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} (T_1). (Rakshitha *et al.*, 2023).

Table 20. Effect of different sources and levels of zinc on availablemicronutrients 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 $ZnSO_4$ @ 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 uptakeof 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 $ZnSO_4$ @ 30 kg ha^{-1} (T_3), followed by treatment of RDF + soil application of Zn EDTA @ 3.0 kg ha^{-1} (T_5), RDF + soil application of $ZnSO_4$ @ 15 kg ha^{-1}

(T_2) and RDF + Soil application of Zn EDTA @ 1.5 kg ha^{-1} (T_4). The lowest nutrient content and uptake were observed in (RDF) 80:40:40 NPK kg ha^{-1} (T_1) 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, Sulfur and Zinc content was observed.

Soil available P, K, S and Zn were highest in RDF + soil application of $ZnSO_4$ @ 30 kg ha^{-1} (T_3) 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} (T_1) treatment.

Therefore, it is concluded that the soil application of $ZnSO_4$ @ 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 uptakein wheat with improvement in soil fertility.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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