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Influence of iron and zinc biofortification on macro and micronutrient dynamics in durum wheat grain and straw cultivated in *Vertic ustochrepts* soil

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Abstract
A field experiment was conducted to evaluate the impact of various combinations of soil, seed, and foliar application of micronutrients on content of N, P, K, Fe and Zn of *durum* wheat (*Triticum durum*) cultivated in *Vertic ustochrepts* soil. The study aimed to determine the most effective method and combination of micronutrient application for optimizing macro-and micronutrient dynamics in durum wheat under the specific agro-edaphic conditions of the study area. Among the treatments, the application of 120:60:00 NPK kg ha^{-1} (RDF) + seed treatment with ZnO + 0.5% $ZnSO_4$ foliar spray (T_{10}) significantly enhanced nitrogen and zinc content in the grain. A significantly higher concentration of phosphorus, potassium, and sulphur in the grain was observed with the application of 120:60:00 NPK kg ha^{-1} (RDF) + seed treatment with $FeSO_4$ and ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray (T_{14}). The significantly higher iron content in both grain and straw was recorded with application 120:60:00 NPK kg ha^{-1} (RDF) + seed soaking with 1% $FeSO_4$ + 0.5% $FeSO_4$ foliar spray (T_6). In straw, treatment T_{14} resulted in significantly higher nitrogen, phosphorus, and sulphur content, while T_6 recorded the higher iron content. The application of treatment T_{10} (120:60:00 NPK kg ha^{-1} (RDF) + seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray) recorded significantly higher zinc content in straw. These findings highlight the potential of integrated micronutrient management, particularly involving seed treatments and foliar sprays, to enhance nutrient content in both grain and straw of durum wheat.

Keywords: Biofortification, iron, zinc, durum wheat, content, macro and micronutrient

Introduction
In India, 59% of kids below the age of five and 54% of pregnant women are anemic, primarily due to iron deficiency, while 38% of children in this age group are stunted, largely due to zinc deficiency. These nutritional deficiencies are major contributors to poor health outcomes and highlight the need for targeted interventions. (IFPRI. 2018) [7] (Indian data Zn and Fe human). Hidden hunger, driven by Zn and Fe deficiencies, affects over half the global population due to reliance on cereal-based diets. These deficiencies are common in humans, animals and plants, posing a major nutritional challenge. Micronutrient deficiencies, particularly of zinc (Zn) and iron (Fe), are a major concern in Indian agriculture, with approximately 49.0% and 12.1% of soils deficient in Zn and Fe, respectively (Arunachalam *et al.*, 2013) [1]. Nation wise research indicates that zinc and iron concentration in the grain is inherently very low, particularly when grown on Zn-Fe deficient soils. The major reason for the wide spread occurrence of Zn-Fe deficiency problems in crop plants is attributed to low solubility of Zn-Fe in soils rather than a low total amount of Zn-Fe. Such deficiencies are especially severe in semi-arid regions, adversely affecting crop productivity. Wheat, a staple crop comprising over 50% of the diet in many developing countries, is inherently low in Fe and Zn. In India, *durum* wheat is predominantly grown in the dry, hot regions of central and peninsular states like Madhya Pradesh, Gujarat, Maharashtra, and Rajasthan, contributing 1.5-2.0 million tonnes annually. Agronomic biofortification, involving soil and foliar application of micronutrients such as $ZnSO_4$ and $FeSO_4$, has emerged as a cost-effective and sustainable strategy to enhance grain micronutrient content and productivity (Velu *et al.*, 2014; Jeong and Guerinot, 2008) [15, 10]. In light of these challenges and opportunities, the present study was undertaken to evaluate the effect of Fe and Zn biofortification on the

productivity of durum wheat grown on *Vertic ustochrepts* soil at the Agricultural Research Station, Anand Agricultural University, Arnej.

Table 1: Initial soil properties of experimental site

Soil Parameter	Value	
	2020-2021	2021-2022
Clay (%)	44.9	45.9
Silt (%)	37.9	36.7
Fine sand (%)	13.8	13.4
Coarse sand (%)	3.35	4.09
Texture	Clay soil	Clay soil
pH (1:2.5)	8.25	8.26
EC (1:2.5) (dSm^{-1})	0.38	0.40
Organic carbon (%)	0.382	0.391
Available N (kg ha^{-1})	114	116
Available P_2O_5(kg ha^{-1})	28.5	27.5
Available K_2O (kg ha^{-1})	380.5	402.2
Micronutriments (ppm)		
DTAP-Fe	5.61	5.40
DTAP-Mn	16.9	12.3
DTAP-Zn	0.58	0.55
DTAP-Cu	1.68	1.33

Materials and Methods

The field experiment for this study was carried out at the Agricultural Research Station farm of Anand Agricultural University, located in Arnej, Gujarat, over two consecutive *rabi* seasons (2020-21 and 2021-22). The research site is situated at the university's off-campus station in Arnej, which falls under Dholka taluka in Ahmedabad district. The experimental field had a flat shaped topography with a gentle slope and found waterlogged condition during monsoon. The soil is representative of the soils of the *bhal* region and is “medium black” soil. The soil chemical analysis indicated that it was low in available nitrogen, available phosphorus whereas high in available potash. With respect to available zinc and iron, the soil of the experimental field was found close to their critical levels.

The experiment was laid out in Randomized Block Design with 3 replications. The fourteen treatments on biofortification Fe and Zn *viz.*, Absolute control (T_1), 120:60:40 NPK kg ha^{-1} (RDF) control (T_2), 120:60:00 NPK kg ha^{-1} (RDF) + soil application $FeSO_4$ (T_3), 120:60:00 NPK kg ha^{-1} (RDF) + seed soaking of $FeSO_4$ (1%) (T_4), 120:60:00 NPK kg ha^{-1} (RDF) + 0.5% $FeSO_4$ foliar spray (T_5), 120:60:00 NPK kg ha^{-1} + seed soaking of $FeSO_4$ (1%) + 0.5% $FeSO_4$ foliar spray (T_6), 120:60:00 NPK kg ha^{-1} + soil application $ZnSO_4$ (T_7), 120:60:00 NPK kg ha^{-1} + seed treatment of ZnO (T_8), 120:60:00 NPK kg ha^{-1} + 0.5% $ZnSO_4$ foliar spray (T_9), 120:60:00 NPK kg ha^{-1} + seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray (T_{10}), 120:60:00 NPK kg ha^{-1} + seed treatment of ZnO+ seed treatment $FeSO_4$ (1%) (T_{11}), 120:60:00 NPK kg ha^{-1} + soil application of Fe and Zn (T_{12}), 120:60:00 NPK kg ha^{-1} + 0.5% $FeSO_4$ foliar spray +0.5% $ZnSO_4$ foliar spray (T_{13}), 120:60:00 NPK kg ha^{-1} + seed treatment of $FeSO_4$+ seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray +0.5% $ZnSO_4$ foliar spray (T_{14}) were studied. A basal application of nitrogen at 60 kg N ha^{-1}, corresponding to 50% of the recommended dose, was incorporated at the time of sowing. while, remaining 50% nitrogen were given in equal two splits, among them, 25% nitrogen (30 kg ha^{-1}) applied at 21 DAS and 25% nitrogen (30 kg ha^{-1}) applied at 45 DAS. The entire recommended dose of phosphorus (60 kg P_2O_5 ha^{-1}) applied as a basal application. Whereas, soil application of 50 kg $FeSO_4$ ha^{-1} and 25 kg $ZnSO_4$ ha^{-1} were applied as basal application. Wheat seeds were treated before sowing by soaking seeds for two hours in $FeSO_4$ (1%) solution as well as seed treatment of Zn was also given with 10 ml ZnO (30%) per kg seed. For foliar application of $FeSO_4$ and $ZnSO_4$ were given with 0.5% $FeSO_4$ and $ZnSO_4$ solution were prepared and applied at three different growths/physiological stages i.e. CRI stages, tillering and milking stage. Wheat var. GADW-3 was taken in *rabi* season for consecutive two years. All treatments were applied over the two years, with the experiment conducted at the same site each year while altering the randomization of treatments. Soil samples were collected from a depth of 0-15 cm in each plot following the wheat harvest. After crop harvest, samples of wheat grains, straw, and roots were collected for analysis. The samples were washed sequentially with a dilute 0.03 N HCl solution, single deionized water, and double deionized water before being air-dried. They were then dried further in paper bags at 70°C in a hot air oven until reaching a constant weight. These samples were ground using a stainless steel Wiley mill to prevent micronutrient contamination and stored in airtight polyethylene bags for further examination.

Results and Discussion

Nitrogen content in grain and straw

The treatment T_9 (120:60:00 NPK kg ha^{-1} (RDF) + 0.5% $ZnSO_4$ foliar spray) and T_{13} (120:60:00 NPK kg ha^{-1} (RDF) + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray) resulted in the higher nitrogen content in grains (2.54 and 2.57%) during the consecutive years, which was statistically on par with all treatments except the absolute control. According to the pooled results, application of 120:60:00 NPK kg ha^{-1} + seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray (T_{10}) achieved the higher nitrogen content (2.55%) in grains but was statistically similar to T_3, T_5, T_6, T_7, T_9, T_{11}, T_{12}, T_{13} and T_{14} treatments.

In case of straw, significant higher nitrogen content (0.637%) observed with application of 120:60:00 NPK kg ha^{-1} + seed treatment of $FeSO_4$+ seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray (T_{14}) and, was par with T_4, T_5, T_6, T_7, T_9, T_{10}, T_{11}, T_{12} and T_{13} treatments in individual years and T_5, T_6, T_7, T_9, T_{10}, T_{11}, T_{12} and T_{13} treatments in the pooled result. An increase in nitrogen (N) content in both the grain and straw of wheat due to the application of various levels of zinc (Zn) can be attributed to the synergistic interaction between N and Zn. This effect may partly result from the positive influence of Zn in promoting vegetative growth, which subsequently enhances the N content in both grain and straw. Additionally, it is evident that plants cannot thrive without sufficient Zn, as it is a critical element for the synthesis of DNA and RNA as well as for metabolizing carbohydrates, lipids, and proteins. According to Keram *et al.* (2014) [12], applying Zn at rates of 2.5, 5, 10 and 20 kg ha^{-1} led to significant increases in grain N content by 10.59%, 18.34%, 21.89% and 23.03%, respectively, compared to the control. These findings are consistent with those reported by Esfandiari and Abdoli (2016) [4], Bandiwaddar *et al.* (2016) [2], Cakmak *et al.* (2010) [3] and Hemantaranjan and Garg (2008) [6].

Phosphorus content in grain and straw

A notable increase in phosphorus content in grains (0.614, 0.602 and 0.608%) was observed with the T_{14} (120:60:00

NPK kg ha^{-1} + seed treatment of $FeSO_4$+ seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray) treatment during individual year. In the first year, this treatment was statistically on par with T_5, T_6, T_7, T_9, T_{10}, T_{11}, T_{12} and T_{13} while in the second year, it was at par with all treatments except T_1 and T_2 treatments. In case of pooled result same trend observed, significant higher phosphorus content (0.608%) in grain observed with T_{14} (120:60:00 NPK kg ha^{-1} + seed treatment of $FeSO_4$+ seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray) and followed by T_5, T_6, T_9, T_{10} and T_{13} treatments.

The result in table-3 revealed that biofortification of Fe and Zn treatments significant influence noticed under treatment T_{14} (120:60:00 NPK kg ha^{-1}(RDF) + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray+0.5% $ZnSO_4$ foliar spray)(2020-21). It was at par with the T_4, T_5, T_6, T_{10}, T_{12} and T_{13} treatments. During the second year (2021-22), application of 120:60:00 NPK kg ha^{-1} (RDF) + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray+0.5% $ZnSO_4$ foliar spray (T_{14}) observed significantly higher P content in straw (0.313%) and it was at par with T_5, T_6, T_8, T_{10}, T_{12} and T_{13} treatments. Pooled result indicated that significantly higher phosphorus content in straw (0.312%) recorded under application of 120:60:00 NPK kg ha^{-1} (RDF) + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray (T_{14}), which was at par to the T_{13} treatment.

Potassium content in grain and straw

Significant higher content of potassium in grain (0.423%) observed with the treatment of 120:60:00 NPK kg ha^{-1} (RDF) + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray+0.5% $ZnSO_4$ foliar spray (T_{14}). It was at par with the T_5, T_6, T_9, T_{10}, T_{11} and T_{13} treatments during 2020-21. Whereas, lower K content in grain (0.311%) recorded under absolute control but, during second year, no significant effect was observed among all treatments.

Pooled result revealed that application of 120:60:00 NPK kg ha^{-1} (RDF) + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray+0.5% $ZnSO_4$ foliar spray (T_{14}) showed its significant superiority in potassium content in grain (0.403%), which was at par to the T_6, T_7, T_8, T_9, T_{10}, T_{11}, T_{12} and T_{13} treatments.

The potassium content in durum wheat straw showed no significant variation across different nutrient management treatments during the 2020-21 and 2021-22 seasons, as well as in the pooled analysis (Table 2).

Sulphur content in grain and straw

The data on pooled result indicated that significantly higher sulphur content in grain (0.170%) was recorded under application of 120:60:00 NPK kg ha^{-1}(RDF) + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray (T_{14}), which was at par to T_6, T_9, T_{10} and T_{13} treatments.

Biofortification of Fe and Zn had a non-significant influence on sulphur content in straw during the individual years (2020-21 and 2021-22). Pooled result revealed that significantly higher sulphur content in straw (0.259%) recorded due to application of 120:60:00 NPK kg ha^{-1}(RDF) + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray (T_{14}), however, it was at par with the all the treatments except absolute control (T_1) and control (T_2).

Iron content in grain and straw

Data summarized table-2 revealed that significantly higher iron content in grain (67.8 ppm) recorded with application of 120:60:00 NPK kg ha^{-1} (RDF) + Seed Soaking of $FeSO_4$ (1%) + 0.5% $FeSO_4$ foliar spray (T_6). However, it was significantly at par with T_3, T_5, T_{13} and T_{14} treatments during first year.

Application of 120:60:00 NPK kg ha^{-1} (RDF) + Seed Soaking of $FeSO_4$ (1%) + 0.5% $FeSO_4$ foliar spray (T_6) recorded significantly higher iron content in grain (68.8 and 68.3 ppm) during second year and in pooled result, respectively. However, it was statistically indistinguishable to the T_5, T_{13} and T_{14} treatments during second year and pooled result. In case of straw, significantly higher iron content (471, 473 and 472 ppm) was noted with application of 120:60:00 NPK kg ha^{-1} (RDF) + Seed Soaking of $FeSO_4$ (1%) + 0.5% $FeSO_4$ foliar spray (T_6) but it was statistically at par with T_3, T_5, T_{12}, T_{13} and T_{14} treatments) during individual year as well in pooled result, respectively. Foliar application ensures that iron is directly absorbed through the leaf cuticle and stomata, bypassing soil-related issues such as pH imbalance or poor soil fertility that might limit iron availability. Once absorbed, iron is translocated via the phloem to different parts of the plant, including the roots, stems, and developing grains. So, it can be concluded that the foliar application of iron during the tillering, CRI, and milking stages significantly enhances iron content and uptake by both grain and straw. This comprehensive approach ensures that the plant has adequate iron throughout its growth, leading to higher productivity and better quality of wheat crop (Keram *et al* 2014) [12]. These results are in agreement with those obtained by Jafarnajadi *et al.* (2024) [8], Nisha (2023) [13], Kaur *et al.* (2020) [11], Yaseen *et al.* (2016) [16], Jalal *et al.* (2020) [9], Goyal (2018) [5] and Bandiwaddar *et al.* (2016) [2]

Zinc content in grain and straw

Application of 120:60:00 NPK kg ha^{-1}(RDF) + Seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray (T_{10}) recorded significantly higher zinc content in grain (46.1 ppm), however, it remained statistically indistinguishable with T_7, T_9 T_{13} and T_{14} treatment during the first year (2020-21). In case of the second year and pooled data, treatment T_{10} (120:60:00 NPK kg ha^{-1} (RDF) + Seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray) noted significantly higher zinc content (54.3 and 50.2 ppm) in grain, respectively, however, it is statistically indistinguishable with the T_9, T_{13} and T_{14} treatments during second year and in pooled result.

Higher Zn concentration in leaves can lead to better grain filling and nutrient content, improving the quality of the harvested grain. (Tiwari 2011) [14]. Keram *et al.* (2014) [12] reported that applying Zn at rates of 1.25, 2.5, 5, 10 and 20 kg ha^{-1} led to significant increases in Zn content in grain by 10.22%, 22.22%, 38.49%, 54.01% and 72.84%, respectively, compared to the control. These findings align with those of Jafarnajadi *et al.* (2024), Nisha (2023) [13], Kaur *et al.* (2020) [11], Yaseen *et al.* (2016) [16] and Jalal *et al.* (2020) [9]

Table 2: Influence of Iron and Zinc biofortification on macronutrient content in grain of *durum* wheat.

Sr. No	Treatments	N (%)		Pooled	P (%)		Pooled	K (%)		Pooled	S (%)		Pooled
		2020-21	2021-22		2021-22	2020-21		2021-22	2020-21		2021-22	2020-21	
T_1	Absolute control	1.89	1.76	1.82	0.432	0.397	0.415	0.311	0.298	0.305	0.145	0.132	0.139
T_2	Control (RDF)	2.27	2.23	2.25	0.519	0.515	0.517	0.330	0.358	0.344	0.144	0.143	0.143
T_3	RDF + Soil application $FeSO_4$	2.43	2.53	2.48	0.529	0.527	0.528	0.377	0.323	0.350	0.154	0.151	0.153
T_4	RDF + Seed soaking of $FeSO_4$ (1%)	2.34	2.35	2.34	0.540	0.537	0.539	0.327	0.336	0.332	0.156	0.155	0.155
T_5	RDF + 0.5% $FeSO_4$ foliar spray	2.45	2.55	2.50	0.572	0.565	0.568	0.387	0.336	0.361	0.162	0.158	0.160
T_6	RDF + Seed soaking of $FeSO_4$ (1%) + 0.5% $FeSO_4$ foliar spray	2.46	2.53	2.50	0.571	0.564	0.567	0.385	0.383	0.384	0.170	0.164	0.167
T_7	RDF + Soil application $ZnSO_4$	2.45	2.30	2.37	0.551	0.535	0.543	0.375	0.364	0.370	0.154	0.152	0.153
T_8	RDF + Seed treatment of ZnO	2.34	2.36	2.35	0.540	0.553	0.547	0.370	0.376	0.373	0.155	0.149	0.152
T_9	RDF + 0.5% $ZnSO_4$ foliar spray	2.55	2.51	2.53	0.560	0.568	0.564	0.382	0.371	0.377	0.165	0.161	0.163
T_{10}	RDF + Seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray	2.54	2.57	2.55	0.570	0.574	0.572	0.393	0.386	0.390	0.171	0.167	0.169
T_{11}	RDF + Seed treatment of ZnO + Seed treatment $FeSO_4$ (1%)	2.40	2.38	2.39	0.556	0.551	0.553	0.381	0.377	0.379	0.150	0.150	0.150
T_{12}	RDF + Soil application of Fe and Zn	2.50	2.40	2.45	0.556	0.545	0.550	0.378	0.374	0.376	0.148	0.147	0.147
T_{13}	RDF + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray	2.51	2.58	2.54	0.611	0.596	0.604	0.419	0.395	0.407	0.170	0.165	0.167
T_{14}	RDF + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray	2.51	2.57	2.54	0.614	0.602	0.608	0.423	0.394	0.409	0.169	0.171	0.170
T	S. Em±	0.09	0.10	0.07	0.024	0.027	0.017	0.015	0.026	0.015	0.01	0.01	0.01
	C. D. at 5%	0.29	0.29	0.20	0.069	0.078	0.050	0.044	NS	0.043	NS	NS	0.014
Y	S. Em±	-	-	0.02	-	-	0.006	-	-	0.005	-	-	0.0019
	C. D. at 5%	-	-	NS	-	-	NS	-	-	NS	-	-	NS
Y×T	S. Em±	-	-	0.09	-	-	0.02	-	-	0.021	-	-	0.007
	C. D. at 5%	-	-	NS	-	-	NS	-	-	NS	-	-	NS
C V%		7.12	7.23	7.17	7.46	8.51	7.99	6.96	12.58	10.07	7.79	8.44	8.11

Table 3: Influence of Iron and Zinc biofortification on macronutrient content in straw of *durum* wheat.

Sr. No	Treatments	N (%)		Pooled	P (%)		Pooled	K(%)		Pooled	S (%)		Pooled
		2020-21	2021-22		2021-22	2020-21		2021-22	2020-21		2021-22	2020-21	
T_1	Absolute control	0.467	0.434	0.450	0.222	0.210	0.216	1.23	1.20	1.22	0.195	0.177	0.186
T_2	Control (RDF)	0.493	0.483	0.488	0.264	0.248	0.256	1.32	1.32	1.32	0.220	0.224	0.222
T_3	RDF + Soil application $FeSO_4$	0.612	0.564	0.588	0.269	0.258	0.264	1.33	1.33	1.33	0.232	0.230	0.231
T_4	RDF + Seed soaking of $FeSO_4$ (1%)	0.584	0.586	0.585	0.281	0.269	0.275	1.34	1.34	1.34	0.235	0.242	0.239
T_5	RDF + 0.5% $FeSO_4$ foliar spray	0.617	0.602	0.609	0.282	0.282	0.282	1.37	1.37	1.37	0.244	0.244	0.244
T_6	RDF + Seed soaking of $FeSO_4$ (1%) + 0.5% $FeSO_4$ foliar spray	0.615	0.618	0.616	0.279	0.282	0.280	1.37	1.36	1.37	0.251	0.245	0.248
T_7	RDF + Soil application $ZnSO_4$	0.588	0.575	0.581	0.267	0.269	0.268	1.35	1.34	1.34	0.242	0.230	0.236
T_8	RDF + Seed treatment of ZnO	0.585	0.587	0.586	0.273	0.279	0.276	1.34	1.35	1.35	0.239	0.236	0.238
T_9	RDF + 0.5% $ZnSO_4$ foliar spray	0.603	0.611	0.607	0.277	0.277	0.277	1.36	1.37	1.36	0.251	0.244	0.248
T_{10}	RDF + Seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray	0.631	0.629	0.630	0.286	0.283	0.285	1.38	1.39	1.38	0.254	0.250	0.252
T_{11}	RDF + Seed treatment of ZnO + Seed treatment $FeSO_4$ (1%)	0.590	0.598	0.594	0.275	0.262	0.268	1.36	1.35	1.35	0.240	0.242	0.241
T_{12}	RDF + Soil application of Fe and Zn	0.588	0.576	0.582	0.278	0.281	0.279	1.36	1.34	1.35	0.241	0.243	0.242
T_{13}	RDF + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray	0.612	0.620	0.616	0.305	0.305	0.305	1.41	1.40	1.41	0.256	0.259	0.258
T_{14}	RDF + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray	0.635	0.639	0.637	0.310	0.313	0.312	1.41	1.40	1.41	0.258	0.260	0.259
T	S. Em±	0.025	0.029	0.018	0.011	0.012	0.008	0.052	0.073	0.045	0.012	0.016	0.009
	C. D. at 5%	0.073	0.085	0.053	0.032	0.035	0.023	NS	NS	NS	NS	NS	0.028
Y	S. Em±	-	-	0.007	-	-	0.003	-	-	0.017	-	-	0.003
	C. D. at 5%	-	-	NS	-	-	NS	-	-	NS	-	-	NS
Y×T	S. Em±	-	-	0.02	-	-	0.011	-	-	0.063	-	-	0.014
	C. D. at 5%	-	-	NS	-	-	NS	-	-	NS	-	-	NS
C V%		7.40	8.75	7.89	6.93	7.68	7.31	6.66	9.45	8.16	8.31	11.85	10.21

Table 4: Influence of Iron and Zinc biofortification on micronutrient content in grain and straw of *durum* wheat.

Sr. No	Treatments	Grain Fe (ppm)		Pooled	Grain Zn (ppm)		Pooled	Straw Fe (ppm)		Pooled	Straw Zn (ppm)		Pooled
		2020-21	2021-22		2021-22	2020-21		2021-22	2020-21		2021-22	2020-21	
T_1	Absolute control	49.5	48.3	48.9	27.9	30.1	29.0	304	300	302	31.1	30.9	31.0
T_2	Control (RDF)	54.2	53.0	53.6	34.0	36.8	35.4	359	355	357	35.9	35.5	35.7
T_3	RDF + Soil application $FeSO_4$	59.8	57.1	58.4	38.0	38.8	38.4	430	445	438	38.3	37.5	37.9
T_4	RDF + Seed soaking of $FeSO_4$ (1%)	56.9	56.6	56.8	36.8	39.8	38.3	397	384	391	37.5	37.3	37.4
T_5	RDF + 0.5% $FeSO_4$ foliar spray	63.8	66.7	65.3	38.2	40.5	39.3	450	457	453	38.4	36.5	37.4
T_6	RDF + Seed soaking of $FeSO_4$ (1%) + 0.5% $FeSO_4$ foliar spray	67.8	68.8	68.3	36.8	43.5	40.2	471	473	472	38.9	36.4	37.6
T_7	RDF + Soil application $ZnSO_4$	56.3	57.3	56.8	41.2	44.7	42.9	366	388	377	39.1	37.2	38.1
T_8	RDF + Seed treatment of ZnO	55.5	56.2	55.9	40.2	44.1	42.1	371	387	379	38.4	37.7	38.1
T_9	RDF + 0.5% $ZnSO_4$ foliar spray	56.0	55.4	55.7	44.2	51.8	48.0	373	387	380	46.8	46.5	46.7
T_{10}	RDF + Seed treatment of ZnO + 0.5% $ZnSO_4$ foliar spray	56.2	55.6	55.9	46.1	54.3	50.2	376	375	376	46.9	46.8	46.8
T_{11}	RDF + Seed treatment of ZnO + Seed treatment $FeSO_4$ (1%)	56.0	55.9	55.9	39.8	40.1	40.0	389	383	386	37.7	36.0	36.9
T_{12}	RDF + Soil application of Fe and Zn	56.8	57.9	57.3	40.6	40.5	40.5	443	443	443	40.9	42.9	41.9
T_{13}	RDF + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray	66.3	67.0	66.6	43.6	52.0	47.8	445	446	445	46.4	46.3	46.3
T_{14}	RDF + Seed treatment of $FeSO_4$ + Seed treatment of ZnO + 0.5% $FeSO_4$ foliar spray + 0.5% $ZnSO_4$ foliar spray	64.9	64.7	64.8	44.2	50.0	47.1	446	446	446	45.1	46.3	45.7
T	S. Em±	3.09	2.99	2.15	1.79	2.21	1.42	24.25	28.16	18.58	2.62	2.95	1.97
	C. D. at 5%	9.00	8.68	6.10	5.22	6.42	4.03	70.50	81.86	52.73	7.62	8.58	5.60
Y	S. Em±	-	-	0.81	-	-	0.53	-	-	7.02	-	-	0.75
	C. D. at 5%	-	-	NS	-	-	1.52	-	-	NS	-	-	NS
Y×T	S. Em±	-	-	3.04	-	-	2.01	-	-	26.27	-	-	2.79
	C. D. at 5%	-	-	NS	-	-	NS	-	-	NS	-	-	NS
C V%		9.15	8.83	8.99	7.89	8.82	8.42	10.46	12.04	11.28	11.32	12.92	12.13

Conclusion

The study confirms that integrated application of Fe and Zn through seed treatments and foliar sprays significantly enhances macro-and micronutrient content in both grain and straw of durum wheat. Treatment T_{10} notably improved nitrogen and zinc content in grain, while T_{14} recorded the highest phosphorus, potassium, and sulphur levels. T_6 proved most effective for iron enrichment in both grain and straw. The synergy between micronutrients and macronutrients, particularly Zn and N, positively influenced plant growth and nutrient uptake. Phosphorus and potassium content also responded well to combined treatments. Sulphur content in straw and grain was highest under T_{14}, showing the benefit of multi-nutrient strategies. Foliar applications, especially at critical growth stages, enhanced nutrient translocation and uptake. Overall, integrated micronutrient management is key to improving wheat yield and nutritional quality in *Vertic ustochrepts* soils.

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