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Nutrient Concentration and Uptake in Wheat (*Triticum aestivum* L.) as Influenced by Metallic Micronutrient Fertilisation in the Ganges–Yamuna Doab

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Original Research Article

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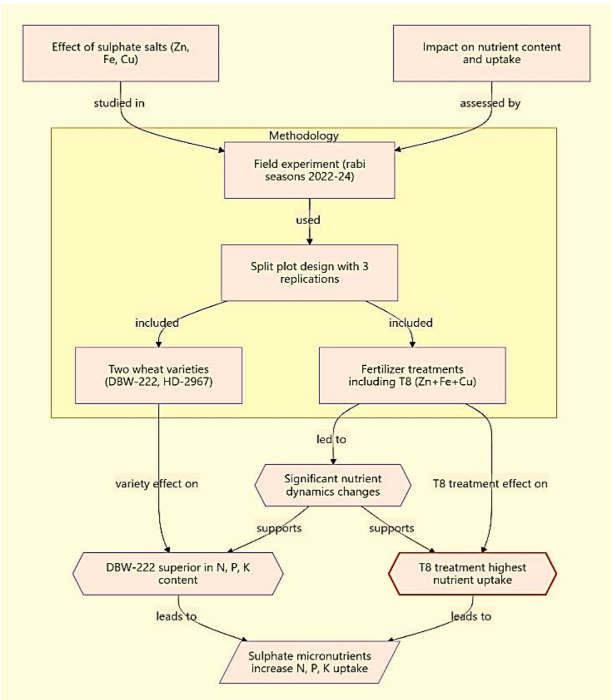
Abstract

A two-year field experiment was conducted during the 2022–23 and 2023–24 rabi seasons at the Student's Instructional Farm of Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India, to evaluate the influence of metallic micronutrient fertilisation on nutrient concentration and uptake in wheat. The experiment was laid out in a split-plot design with three replications. Two wheat varieties, DBW-222 and HD-2967, were assigned to the main plots, while nutrient management treatments involving soil and foliar application of zinc sulphate, iron sulphate and copper sulphate were assigned to the subplots. The results indicated varietal and nutrient-management effects on nitrogen, phosphorus and potassium concentration and uptake in grain and straw. On a pooled basis, DBW-222 recorded higher nutrient concentration than HD-2967, with 2.33% N, 0.371% P and 0.49% K in grain, and 0.770% N, 0.113% P and 1.189% K in straw. The same variety also recorded greater pooled nutrient uptake in grain, with 143.70 kg N/ha, 22.98 kg P/ha and 30.28 kg K/ha. Among nutrient management practices, soil application of zinc, iron and copper through $ZnSO_4 \cdot 7H_2O$ at 20 kg/ha, $FeSO_4 \cdot 7H_2O$ at 12 kg/ha and $CuSO_4 \cdot 5H_2O$ at 2 kg/ha recorded the highest pooled nutrient uptake. This treatment recorded 147.94 kg N/ha, 28.17 kg P/ha and 35.04 kg K/ha in grain, and 49.85 kg N/ha, 11.28 kg P/ha and 79.13 kg K/ha in straw. The findings suggest that combined soil application of zinc, iron and copper sulphates improved nutrient concentration and uptake in wheat under the studied agro-climatic conditions of the Ganges–Yamuna Doab.

Graphical Abstract



Keywords: Wheat; Triticum aestivum; micronutrients; zinc sulphate; iron sulphate; copper sulphate; nutrient concentration; nutrient uptake; nitrogen; phosphorus; potassium; Ganges–Yamuna Doab.

1. Introduction

Wheat (*Triticum aestivum* L.) serves as a staple food worldwide because of its nutritional composition, providing essential carbohydrates, proteins and fats required for human health (Ammar et al., 2023). Commonly referred to as the "King of Cereals", wheat belongs to the Poaceae family and is a valuable source of carbohydrates, proteins, minerals and vitamins. India ranks as the second-largest producer of wheat, achieving record production of 113.29 million tonnes during 2023–24, with Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Rajasthan, Bihar and Gujarat as the major growing states. The country contributes 71.5% of South Asia's and 32.5% of Asia's total wheat production, accounting for 14.3% of global output. Globally, wheat production in 2023 reached 798.97 million tonnes, cultivated over an area of 220.40 million hectares, with an average productivity of 3.68 t/ha (Food and Agriculture Organization of the United Nations, 2025). Considering the challenges posed by a growing global population and climate change, wheat production must be doubled by 2050 to meet future food demand (Mottaleb et al., 2023).

Soil fertility status varies significantly across regions, necessitating the application of both organic and inorganic fertilisers to achieve optimal crop yields. In addition to macronutrients such as nitrogen (N), phosphorus (P) and potassium (K), micronutrient availability is equally vital for sustaining crop productivity. Among these, zinc (Zn), iron (Fe) and copper (Cu) play important roles in improving wheat yield and associated yield attributes, including nutrient concentration (Sachan & Siddiqui, 2025). Zinc is an essential micronutrient required by plants and animals, including humans, because it is involved in a wide range of physiological and biochemical processes. In plants, zinc plays a vital role in enzyme activation, protein synthesis, chlorophyll formation and various metabolic pathways (Singh et al., 2018). Zinc application in agriculture has been shown to enhance crop yield and quality (Hassan et al., 2019), whereas zinc deficiency results in significant yield losses and deterioration in produce quality (Wang et al., 2018). Deficiencies of iron and copper have developed in almost 30% of cultivated soils worldwide and subsequently in the crops grown on them.

Numerous experiments have been conducted on the application of trace elements worldwide, and their results have shown that such application not only increases quantitative and qualitative yield but also increases trace-element concentrations in wheat grains (Ram et al., 2024). Significant improvement in Fe and Zn content through the external application of salts containing Fe and Zn has been reported in wheat grains (Pataco et al., 2017). As Zn has higher mobility in wheat phloem (Haslett et al., 2001), foliar application of Zn is considered the most effective method for improving Zn concentration in wheat grain. Reports indicate that foliar application of Zn salts can increase grain Zn concentration up to three- to four-fold, depending on soil status and climatic conditions. Although Fe mobility within the phloem is intermediate, reports indicate appreciable re-translocation of Fe from the shoot to the grain in wheat (Garnett & Graham, 2005). Sulphatic fertilisers or salts of zinc, iron and copper micronutrients have been reported to increase nutrient concentration and uptake in plant parts in various studies.

However, information remains limited on how soil and foliar application of Zn, Fe and Cu, applied alone and in combination, affects N, P and K concentration and uptake in grain and straw of wheat varieties under the Ganges–Yamuna Doab. This gap is relevant because nutrient uptake responses may vary with variety, application method and local soil fertility status.

Therefore, the present study was conducted to evaluate the effect of soil and foliar application of Zn, Fe and Cu fertilisers on N, P and K concentration and uptake in two wheat varieties (DBW-222 and HD-2967) under the agro-climatic conditions of the Ganges–Yamuna Doab.

2. Materials and Methods

2.1 Experimental Site

The experiment was conducted at the Student's Instructional Farm (SIF) of Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, India, situated at 26.493729° N latitude and 80.294382° E longitude, and at an altitude of 125.9 m above mean sea level (MSL), during two consecutive rabi seasons, 2022–23 and 2023–

24. The climate of the site is subtropical, with maximum and minimum temperatures ranging from 45°C to 4°C. The soil was sandy loam in texture, with a pH of 7.7 and available N, P and K contents of 186.5 kg/ha, 17.5 kg/ha and 319.9 kg/ha, respectively.

2.2 Treatment Details

The experiment was laid out in a split-plot design and replicated three times. The main plot comprised two widely cultivated wheat varieties, namely DBW-222 (V1) and HD-2967 (V2). Subplot treatments included the following nutrient management strategies: control-RDF (T0); RDF + soil application of Zn through ZnSO4. 7H2O @ 20 kg/ha (T1); RDF + foliar spray of Zn as 1.0% ZnSO4. 7H2O at tillering and booting stages (T2); RDF + soil application of Fe through FeSO4.7H2O @ 12 kg/ha (T3); RDF + foliar spray of Fe as 1.5% FeSO4. 7H2O at tillering and booting stages (T4); RDF + soil application of Cu through CuSO4. 5H2O @ 2 kg/ha (T5); RDF + foliar spray of Cu as 0.1 % CuSO4. 7H2O at tillering and booting stages (T6); RDF + foliar spray of (Zn + Fe) as 1.0% ZnSO4. 7H2O and 1.5% FeSO4. 7H2O at tillering and booting stages (T7); RDF + soil application of (Zn + Fe + Cu) through ZnSO4. 7H2O @ 20 kg/ha, FeSO4. 7H2O @ 12 kg/ha and CuSO4.5H2O @ 2 kg/ha (T8); and RDF + foliar application of (Zn + Fe + Cu) as 1.0 % ZnSO4. 7H2O, 1.5% FeSO4. 7H2O and 0.1% CuSO4. 5H2O at tillering and booting stages (T9). The crop was fertilised with the recommended dose of fertilisers (RDF) @ 120:60:40 N2O, P2O5 and K2O kg/ha. A recommended seed rate of 100 kg/ha was used (Megerssa et al., 2023). Sowing was done in lines 22.5 cm apart.

Phosphorus was applied at 60 kg P2O5/ha through di-ammonium phosphate (DAP). Nitrogen (N) was applied at the recommended dose of 120 kg/ha. As DAP supplied approximately 23.5 kg N/ha, the remaining N was supplied through urea (46% N) to complete the recommended dose. Nitrogen was applied in two equal splits, with half applied at the time of sowing and the remaining half applied as top dressing. Muriate of potash (MOP) was applied at sowing at 40 kg K2O/ha. Soil application of zinc sulphate, iron sulphate and copper sulphate was carried out as per the treatments before sowing, except in the control. Foliar sprays of zinc sulphate, iron sulphate and copper sulphate were applied as per the treatments using a spray volume of 300 litres of water/ha. Foliar spraying of the micronutrient fertilisers was done twice: the first spray at the tillering stage and the second spray at the booting stage.

2.3 Nutrient Analysis

For the estimation of total N, P and K contents in wheat straw, the following methods and procedures were followed.

Nutrient	Method Used	Instrument used
Nitrogen (N)	*Kjeldahl Method*	Kjeldahl Unit
Phosphorus (P)	*Vanadomolybdophosphoric Yellow Colour Method*	Spectrophotometer
Potassium (K)	*Wet Digestion Method*	AAS

2.3.1 Nutrient Uptake in Grain

Nutrient uptake in grain was estimated using the following formula-

$$\text{Nutrient uptake(kg/ha)} = \frac{\text{Nutrient conc. in grain (\%)} \times \text{Grain Yield(kg/ha)}}{100}$$

2.3.2 Nutrient Uptake in Straw

Nutrient uptake in straw was estimated using the following formula-

$$\text{Nutrient uptake(kg/ha)} = \frac{\text{Nutrient conc. in straw (\%)} \times \text{Straw Yield (kg/ha)}}{100}$$

The OP-STAT web server was used to carry out statistical analysis.

3. Results and Discussion

3.1 N Content (%) and Uptake (kg/ha) in Wheat Grain and Straw

The N content (%) and uptake (kg/ha) in wheat grain and straw are presented in Table 1. Grain N content ranged from 2.32% to 2.35% for DBW-222, which was consistently higher than HD-2967 (2.04–2.05%) (Fig. 1). Among the nutrient management treatments, the highest pooled grain N content (2.34%) was recorded with soil application of (Zn + Fe + Cu) through $ZnSO_4.7H_2O$ @ 20 kg/ha, $FeSO_4.7H_2O$ @ 12 kg/ha and $CuSO_4.5H_2O$ @ 2 kg/ha, followed by T9 (2.30%) and T7 (2.24%), indicating enhanced nitrogen assimilation under these treatments. The control treatment (T0) showed the lowest grain N content (2.04%), emphasising the beneficial effect of nutrient application. Similarly, on a pooled-data basis, straw N content followed a trend similar to that of grain N content, with DBW-222 (0.770%) surpassing HD-2967 (0.675%) (Fig. 2). Among the treatments, the highest straw N content was observed in T8 (0.772%), followed by T9 (0.762%) and T7 (0.740%), indicating improved nutrient mobilisation and utilisation efficiency. The lowest straw N content was noted in the control (T0) (0.675%), underscoring the importance of nutrient supplementation in enhancing nitrogen concentration in plant residues.

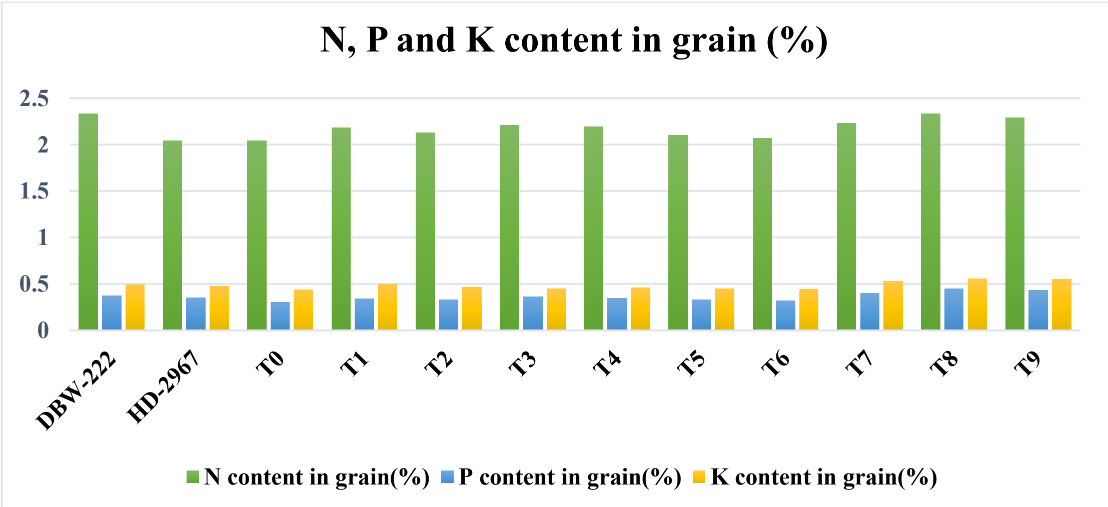


Fig. 1. N, P and K content in grain at pooled (%)

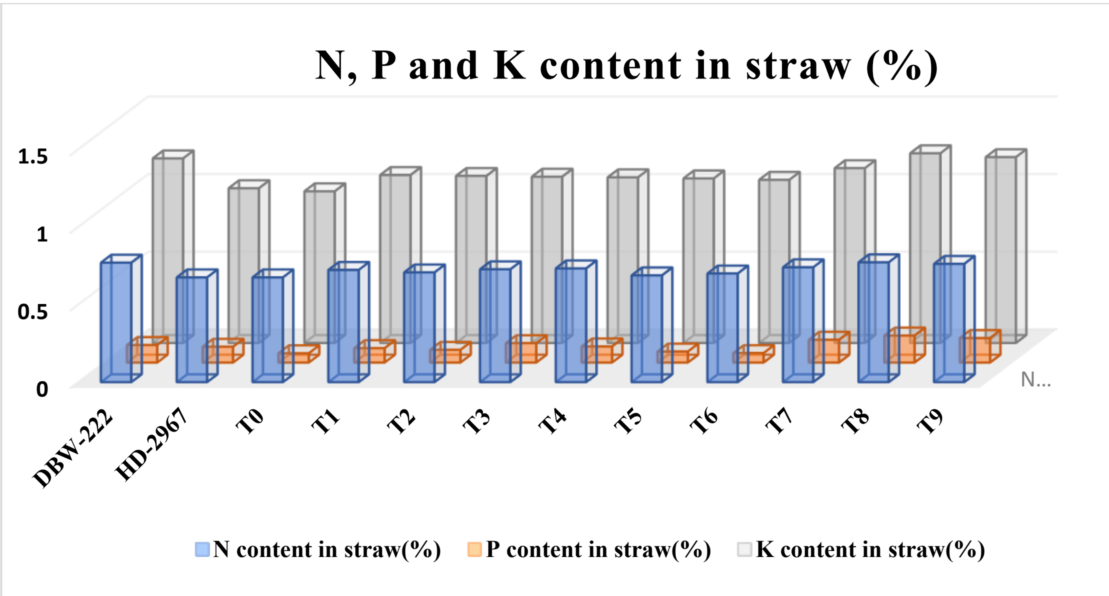


Fig. 2. N, P and K content in straw at pooled (%)

Table 1. Nitrogen (N) content and uptake in wheat grain and straw as influenced by wheat varieties and nutrient management

	N content in grain (%)			N uptake in grain (kg ha^{-1})			N content in straw (%)			N uptake in straw (kg ha^{-1})		
Treatments	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**
Wheat Varieties												
V_1	2.35	2.32	2.33	145.23	142.16	143.70	0.774	0.766	0.770	48.31	50.69	49.50
V_2	2.05	2.04	2.04	108.69	106.36	107.53	0.678	0.672	0.675	40.31	42.36	41.34
SE(m) ±	0.003	0.003	0.003	0.96	0.53	0.74	0.001	0.001	0.001	0.81	0.50	0.65
CD (P =0.05)	0.019	0.021	0.019	6.29	3.50	4.90	0.005	0.006	0.004	5.32	3.28	4.25
Nutrient Management												
T_0	2.05	2.04	2.04	104.87	102.75	103.81	0.677	0.673	0.675	39.41	41.51	40.46
T_1	2.20	2.18	2.19	129.39	126.87	128.13	0.727	0.723	0.723	44.64	46.96	45.80
T_2	2.15	2.13	2.14	122.52	120.23	121.37	0.708	0.703	0.707	44.01	46.09	45.05
T_3	2.22	2.21	2.22	125.23	122.80	124.02	0.728	0.725	0.727	44.96	47.34	46.15
T_4	2.21	2.19	2.20	122.74	120.54	121.64	0.733	0.730	0.733	45.00	47.33	46.17
T_5	2.14	2.10	2.12	117.37	113.98	115.67	0.697	0.682	0.688	42.20	43.91	43.06
T_6	2.11	2.07	2.09	115.42	111.71	113.57	0.705	0.693	0.700	42.04	43.85	42.95
T_7	2.25	2.23	2.24	137.96	135.14	136.55	0.743	0.737	0.740	44.98	47.38	46.18
T_8	2.34	2.33	2.34	149.18	146.70	147.94	0.775	0.768	0.772	48.61	51.10	49.85
T_9	2.38	2.29	2.30	144.92	141.89	143.41	0.765	0.757	0.762	47.27	49.75	48.51
SE(m) ±	0.027	0.016	0.021	2.10	1.64	1.66	0.009	0.005	0.007	1.22	0.80	0.92
CD (P =0.05)	0.078	0.045	0.060	6.06	4.72	4.79	0.026	0.015	0.020	3.50	2.31	2.66
Interaction												
V x T	2.20	2.18	2.19	126.96	124.26	125.61	0.726	0.719	0.722	44.31	46.52	45.42
SE(m) ±	0.009	0.010	0.009	3.04	1.69	2.36	0.003	0.003	0.002	2.57	1.58	2.05
CD (P =0.05)	NS	NS	NS	9.71	7.15	7.64	NS	NS	NS	NS	NS	NS

CD=Critical Difference; NS=Non-significant

Grain N uptake exhibited significant variation between varieties, with DBW-222 (pooled average 143.70 kg/ha) outperforming HD-2967 (107.53 kg/ha) (Fig. 3). Nutrient management treatments markedly influenced grain N uptake, with maximum pooled uptake under T8 (147.94 kg/ha), followed closely by T9 (143.41 kg/ha). Nitrogen uptake in straw, on a pooled basis, was significantly higher in DBW-222 (49.50 kg/ha) than in HD-2967 (41.34 kg/ha) (Fig. 4). Among the nutrient management treatments, maximum straw N uptake was recorded under T8 (49.85 kg/ha), closely followed by T9 (foliar application of Zn + Fe + Cu as 1.0% ZnSO4. 7H2O, 1.5% FeSO4. 7H2O and 0.1% CuSO4. 5H2O at tillering and booting stages) (48.51 kg/ha) and T7 (foliar application of Zn + Fe as 1.0% ZnSO4. 7H2O and 1.5% FeSO4. 7H2O at tillering and booting stages) (46.18 kg/ha). Minimum straw N uptake occurred under the control (T0) (40.46 kg/ha), demonstrating the role of nutrient treatments in augmenting total nitrogen uptake and contributing positively to overall biomass nutrient enrichment. These results highlight that the combined application of zinc, iron and copper, particularly through soil and foliar supplementation, enhanced nitrogen content in grain, likely because of improved root metabolism, nitrogen uptake and protein biosynthesis facilitated by micronutrient cofactors. Similar results were also reported by Guo et al. (2021) and Klikocka and Marks (2018).

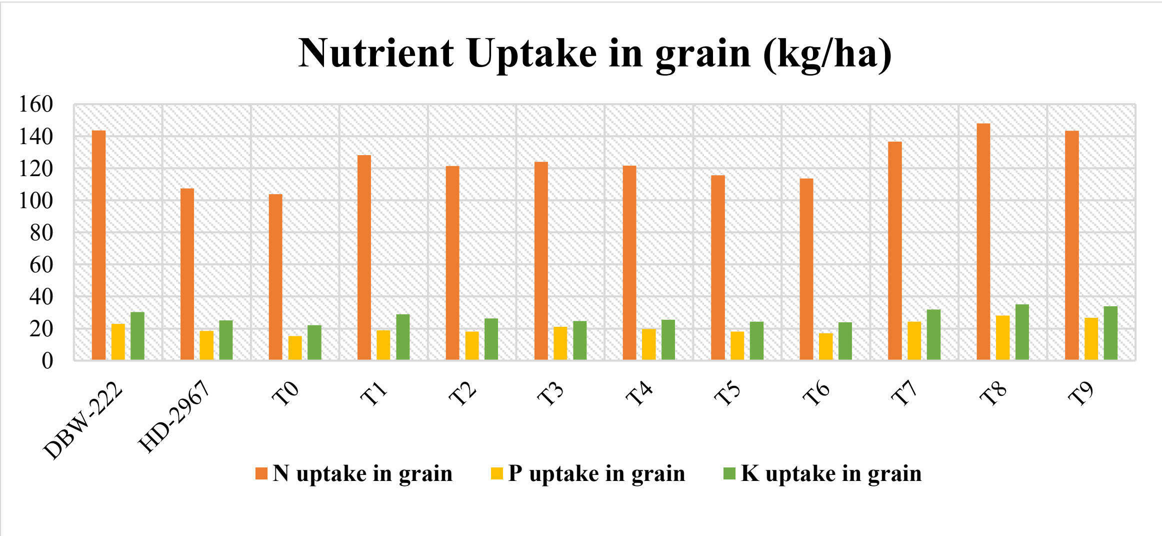


Fig. 3. Nutrient uptake in grain at pooled (kg/ha)

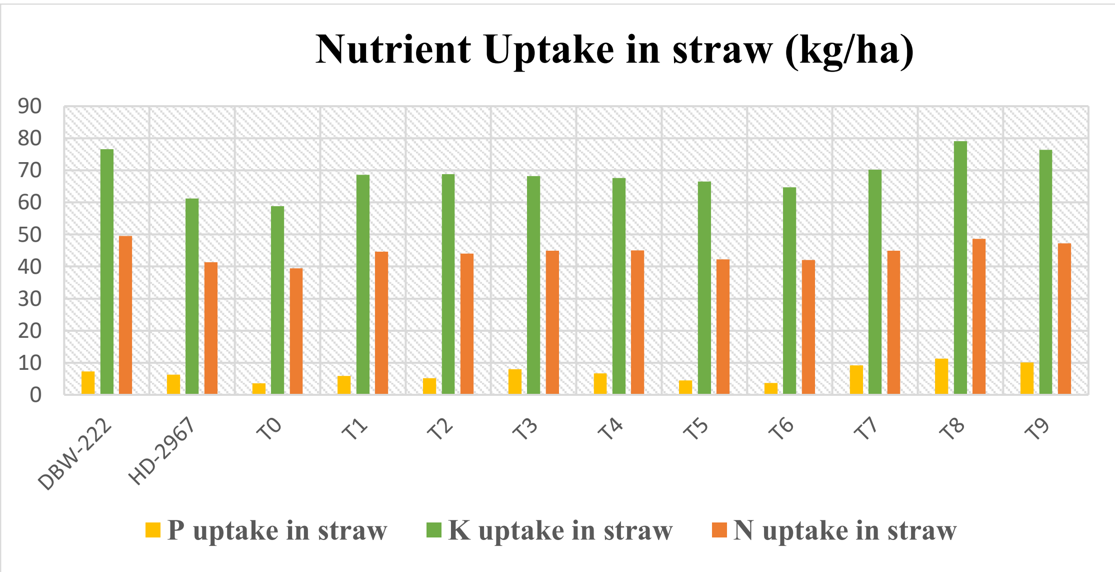


Fig. 4. Nutrient uptake in straw at pooled (kg/ha)

Table 2. Phosphorus (P) content and uptake in wheat grain and straw as influenced by wheat varieties and nutrient management

	P content in grain (%)			P uptake in grain (kg ha^{-1})			P content in straw (%)			P uptake in straw (kg ha^{-1})		
Treatments	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**
Wheat Varieties												
V_1	0.349	0.392	0.371	21.79	24.16	22.98	0.106	0.121	0.113	6.58	7.96	7.27
V_2	0.335	0.368	0.352	17.78	19.31	18.55	0.096	0.108	0.102	5.78	6.90	6.34
SE(m) ±	0.002	0.001	0.001	0.18	0.14	0.16	0.000	0.000	0.000	0.16	0.09	0.13
CD (P =0.05)	0.013	0.007	0.010	1.22	0.91	1.05	0.001	0.002	0.001	NS	0.58	0.83
Nutrient Management												
T_0	0.288	0.320	0.304	14.64	16.07	15.35	0.056	0.063	0.060	3.24	3.90	3.57
T_1	0.323	0.358	0.340	18.07	19.84	18.96	0.088	0.098	0.093	5.39	6.44	5.92
T_2	0.314	0.349	0.331	17.34	19.08	18.21	0.077	0.087	0.082	4.75	5.65	5.20
T_3	0.344	0.383	0.363	20.14	22.15	21.14	0.117	0.134	0.125	7.22	8.70	7.96
T_4	0.328	0.365	0.347	18.70	20.61	19.66	0.098	0.110	0.104	6.05	7.24	6.65
T_5	0.315	0.350	0.332	17.21	18.92	18.06	0.068	0.075	0.071	4.10	4.85	4.47
T_6	0.300	0.334	0.317	16.41	17.97	17.19	0.057	0.064	0.061	3.42	4.04	3.73
T_7	0.379	0.421	0.400	23.09	25.40	24.25	0.137	0.157	0.147	8.31	10.06	9.18
T_8	0.423	0.470	0.447	26.78	29.56	28.17	0.163	0.186	0.174	10.21	12.35	11.28
T_9	0.409	0.451	0.43	25.48	27.79	26.63	0.148	0.168	0.158	9.13	11.06	10.10
SE(m) ±	0.003	0.004	0.002	0.25	0.32	0.19	0.001	0.001	0.001	0.17	0.16	0.15
CD (P =0.05)	0.007	0.012	0.006	0.72	0.92	0.56	0.004	0.003	0.002	0.49	0.46	0.44
Interaction												
V x T	0.342	0.380	0.361	19.79	21.74	20.76	0.101	0.114	0.107	6.18	7.43	6.80
SE(m) ±	0.006	0.003	0.005	0.59	0.44	0.51	0.001	0.001	0.000	0.52	0.28	0.40
CD (P =0.05)	0.014	NS	0.011	1.33	1.45	1.10	NS	0.005	0.003	NS	NS	NS

Table 3. Potassium (K) content and uptake in wheat grain and straw as influenced by wheat varieties and nutrient management

	K content in grain (%)			K uptake in grain (kg ha^{-1})			K content in straw (%)			K uptake in straw (kg ha^{-1})		
Treatments	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**
Wheat Varieties												
V_1	0.467	0.513	0.49	28.98	31.57	30.28	1.138	1.240	1.189	71.02	82.08	76.55
V_2	0.454	0.499	0.477	24.07	26.13	25.10	0.955	1.038	0.997	56.92	65.60	61.26
SE(m) ±	0.002	0.002	0.002	0.17	0.25	0.20	0.001	0.004	0.001	1.21	0.95	1.08
CD (P =0.05)	NS	0.014	0.010	1.13	1.66	1.34	0.006	0.025	0.009	7.96	6.26	7.10
Nutrient Management												
T_0	0.417	0.459	0.438	21.29	23.06	22.17	0.935	1.019	0.977	54.55	62.99	58.77
T_1	0.471	0.520	0.496	27.57	30.08	28.82	1.036	1.128	1.082	63.70	73.59	68.65
T_2	0.444	0.488	0.466	25.24	27.47	26.35	1.029	1.122	1.076	63.97	73.72	68.84
T_3	0.429	0.470	0.450	23.72	25.76	24.74	1.025	1.117	1.071	63.21	73.12	68.16
T_4	0.434	0.479	0.457	24.33	26.51	25.42	1.022	1.114	1.067	62.79	72.41	67.60
T_5	0.428	0.471	0.449	23.37	25.44	24.41	1.014	1.105	1.060	61.69	71.21	66.46
T_6	0.422	0.464	0.443	23.06	24.95	24.00	1.006	1.095	1.051	60.02	69.48	64.75
T_7	0.504	0.555	0.529	30.62	33.30	31.96	1.078	1.175	1.126	65.06	75.42	70.24
T_8	0.531	0.583	0.557	33.54	36.55	35.04	1.175	1.269	1.222	73.80	84.46	79.13
T_9	0.524	0.575	0.549	32.56	35.39	33.98	1.148	1.246	1.197	70.91	81.98	76.44
SE(m) ±	0.005	0.005	0.003	0.32	0.38	0.24	0.011	0.012	0.008	1.69	1.51	1.40
CD (P =0.05)	0.014	0.016	0.010	0.93	1.11	0.68	0.030	0.035	0.024	4.87	4.36	4.04
Interaction												
V x T	0.462	0.506	0.483	26.53	28.85	27.69	1.047	1.139	1.093	63.97	73.84	68.90
SE(m) ±	0.007	0.007	0.005	0.55	0.80	0.65	0.003	0.012	0.004	3.84	3.02	3.43
CD (P =0.05)	NS	NS	NS	1.55	1.96	1.33	0.043	0.053	0.035	8.84	7.59	7.53

3.2 P Content (%) and Uptake (kg/ha) in Wheat Grain and Straw

The P content (%) and uptake (kg/ha) in wheat grain and straw are presented in Table 2. Phosphorus content in grain was higher in DBW-222 (0.371%) than in HD-2967 (0.352%) on a pooled basis. Among the nutrient management treatments, the highest pooled grain P content was recorded in T8 (0.447%), followed by T9 (0.430%) and T7 (0.400%), clearly reflecting improved P assimilation due to the applied nutrient combinations. Similarly, wheat straw P content followed the trend observed in grain, with DBW-222 (0.113%) significantly exceeding HD-2967 (0.102%). Among the nutrient management practices, the highest straw P content was registered in T8 (0.174%) on a pooled basis. The control treatment (T0) showed the lowest straw P content (0.060%).

On a pooled-data basis, DBW-222 exhibited significantly greater grain P uptake (22.98 kg/ha) than HD-2967 (18.55 kg/ha). Nutrient treatments demonstrated distinct effects, with T8 recording the maximum pooled grain P uptake (28.17 kg/ha), followed by T9 (26.63 kg/ha) and T7 (24.25 kg/ha). The control treatment (T0) consistently showed the minimum grain P uptake (15.35 kg/ha), underscoring the role of nutrient supplementation in enhancing grain P assimilation. Pooled phosphorus uptake in straw was superior in DBW-222 (7.27 kg/ha) compared with HD-2967 (6.34 kg/ha). Among the nutrient management treatments, T8 recorded the highest straw P uptake (11.28 kg/ha). These findings are in line with those of Janardhan and Rani (2019).

3.3 K Content (%) and Uptake (kg/ha) in Wheat Grain and Straw

The K content (%) and uptake (kg/ha) in wheat grain and straw are presented in Table 3. Potassium content in grain was consistently higher in DBW-222 (0.490%) than in HD-2967 (0.477%) on a pooled-data basis (Fig. 1). Among the nutrient management treatments, the maximum pooled grain K content (0.557%) was recorded in T8, followed by T9 (0.549%) and T7 (0.529%), indicating an enhanced capacity for K uptake due to these nutrient combinations. The control treatment (T0) exhibited the lowest grain K content (0.438%). Similarly, straw potassium content was significantly higher in DBW-222 (1.189%) than in HD-2967 (0.997%). Among the nutrient management treatments, the highest straw K content was observed in T8 (1.222%), followed by T9 (1.197%), reflecting efficient mobilisation and utilisation of potassium due to nutrient management. The control treatment (T0) recorded the lowest straw K content (0.977%), indicating that sulphate salt application significantly influenced potassium enrichment in straw biomass.

Grain K uptake varied significantly between varieties, with DBW-222 (pooled average 30.28 kg/ha) surpassing HD-2967 (25.10 kg/ha). Nutrient management treatments also notably affected grain K uptake, with soil application of (Zn + Fe + Cu) through ZnSO4. 7H2O @ 20 kg/ha, FeSO4. 7H2O @ 12 kg/ha and CuSO4. 5H2O @ 2 kg/ha (T8) achieving the highest pooled uptake (35.04 kg/ha), followed closely by foliar application of Zn + Fe + Cu as 1.0% ZnSO4. 7H2O, 1.5% FeSO4. 7H2O and 0.1% CuSO4. 5H2O at tillering and booting stages (T9) (33.98 kg/ha). The lowest grain K uptake occurred in the control (T0) (22.17 kg/ha), highlighting the role of nutrient management in promoting potassium assimilation in grain. Similarly, on a pooled-data basis, DBW-222 exhibited substantially greater straw K uptake (76.55 kg/ha) than HD-2967 (61.26 kg/ha). Nutrient treatments showed clear variations, with the highest pooled straw K uptake recorded under T8 (79.13 kg/ha). Minimum straw K uptake was consistently found under the control (T0) (58.77 kg/ha on a pooled basis), demonstrating the substantial benefit of nutrient management strategies in enhancing biomass potassium accumulation. Overall, these findings indicate that the combined application of Zn, Fe and Cu, especially through soil application, was associated with greater potassium uptake in wheat grain, with DBW-222 being more responsive across all treatment regimes. Similar findings have also been reported by Bashir et al. (2023) and Brhane et al. (2017).

4. Conclusions

The present two-year field study showed that nutrient concentration and uptake in wheat were influenced by both varietal response and metallic micronutrient fertilisation under the agro-climatic conditions of the Ganges–Yamuna Doab. Among the two wheat varieties, DBW-222 recorded higher nitrogen, phosphorus and potassium concentration and uptake in both grain and straw than HD-2967. On a pooled basis, DBW-222 recorded 2.33% N, 0.371% P and 0.49% K in grain, and 0.770% N, 0.113% P and 1.189% K in straw. Among the nutrient management treatments, soil application of zinc, iron and copper through $ZnSO_4{\cdot}7H_2O$ at 20 kg/ha,

$FeSO_4 \cdot 7H_2O$ at 12 kg/ha and $CuSO_4 \cdot 5H_2O$ at 2 kg/ha recorded the highest pooled uptake values. This treatment recorded 147.94 kg N/ha, 28.17 kg P/ha and 35.04 kg K/ha in grain, and 49.85 kg N/ha, 11.28 kg P/ha and 79.13 kg K/ha in straw. These results indicate that combined soil application of zinc, iron and copper sulphates can support improved nutrient accumulation in wheat, particularly in DBW-222, within the soil and management conditions evaluated in this experiment. The response pattern also suggests that nutrient management decisions should consider varietal performance together with the method of micronutrient application for comparable wheat-production environments and similar field conditions.

5. Limitations

This study was conducted at one experimental site during two rabi seasons; therefore, the findings mainly represent the soil, climate and crop-management conditions of the Student's Instructional Farm at Kanpur. The assessment was restricted to nitrogen, phosphorus and potassium concentration and uptake in wheat grain and straw, while detailed zinc, iron and copper concentration in plant tissues was not presented. Only two wheat varieties, DBW-222 and HD-2967, were included, so varietal responses may differ when other genotypes are grown. The experiment evaluated selected soil and foliar application rates of zinc, iron and copper sulphates, without testing a wider range of dose combinations or application timings. The residual effects of micronutrient application on soil nutrient balance, succeeding crops and long-term productivity were also not assessed. Multi-location and multi-season evaluation would help confirm the consistency of the observed responses under wider production conditions and management systems in future studies and field validation.

Disclaimer (Artificial Intelligence)

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

Conflict of Interest

Authors have declared that no conflict of interest exists.

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