Effect of 4R stewardship based potassium fertilization on the harvest index of iron, zinc and copper in wheat

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Effect of 4R stewardship based potassium fertilization on the harvest index of iron, zinc and copper in wheat

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ABSTRACT

Two-year field experiments were conducted at the research farm of ICAR–Indian Agricultural Research Institute, New Delhi, to study the effect of 4R nutrient stewardship based potassium (K) fertilization on the uptake and translocation of Zn, Fe & Cu in wheat. Results from the study revealed that the rate of K application and its time of application have a significant role in the uptake and translocation of Fe, Cu, and Zn in wheat. The source of K fertilizer had a non-significant effect. Interestingly the concentration of Fe, Cu, and Zn in grain improved with increasing the dose of K application upto 60 kg K_2O/ha. Similarly, two split applications of 60 kg K_2O/ha recorded higher grain nutrient concentration (Fe, Zn & Cu) than basal application. In the absence of top dressing of K fertilizer, the foliar application of 2.5% K recorded a statistically equal effect to that of top dressing. The harvest index of Zn (52.3-57.4%), Fe (21-26.5%) and Cu (27.5-31.3%) shows more than 1/2th, 1/5th and 1/3th of the absorbed Zn, Fe and Cu is remobilized to grain respectively. The remobilization of Zn, Fe, and Cu from straw to grain is enhanced by the best potassium fertilization management. Thus, Fe, Zn & Cu bio-fortification through balanced application of potassium fertilizer based on 4R nutrient stewardship is an effective approach to fight hidden hunger/ malnutrition.

Key words Wheat, Potassium, Iron, Zinc, Copper, Agronomic bio-fortification

Introduction

Zinc (Zn) deficiency is widespread in agricultural soils; about 50% of cereal-growing soils are low in plant available Zn [1]. Similarly, 19.2% and 11.4% of soil are low in iron (Fe) and Copper (Cu) respectively [2]. In deficit soil, the availability of these micro-nutrients is not sufficient to plant needs which leads to widespread micro-nutrient deficiency and subsequently poor grain quality [3]. A large portion of the global population is affected by malnutrition. For example, 30% of the population in South-Asia is at the risk of Zn deficiency [4]. In South-Asian countries viz., India, Pakistan, Bangladesh, Sri Lanka, and Nepal the prevalence of Zn insufficiency is more in children, pregnant and lactating women in [5]. Similarly, 24.8% of the global population (1.62 billion people) is suffering from anaemia, a disease in humans due to Fe deficiency [6].

Increasing cationic micro-nutrient concentration in staple food crops like rice and wheat is gaining importance in recent years with increasing awareness about nutritional security. The concentration of cationic micro-nutrients in the grain is influenced by several factors including fertilizer management, weather, soil fertility, organic matter, variety, etc. [7]. Among the several approaches of bio-fortification, agronomic bio-fortification was found very effective in improving the nutritional quality of grain in a short period [8]. The interaction between the nutrients plays a major role in determining the effectiveness of agronomic bio-fortification in various crops [9]. 4R nutrient stewardship (right dose, right time, right method, right source) based fertilizer application helps in harvesting synergistic interaction between most of the nutrients [10].

Potassium (K), a macro-nutrient taken up by a wheat crop in large quantity in its life cycle and K plays a major role in many of the physiological and bio-chemical processes of the plant [11]. Last two decades many researchers have reported positive responses of wheat crop to K fertilization in the rice-wheat cropping system of the Indo-Gangetic plain. Most of the K research in RWCS is mostly concentrated on determining the optimum dose and time of application. No studies were conducted to know the relationship between K fertilization and micro-nutrient uptake. Thus we conducted field trials with the objective of determining the relationship between potassium fertilization and micro-nutrient uptake in wheat crop.

MATERIALS AND METHODS

Details of the experimental site

The field trial was conducted during the *rabi* season of 2015-16 and 2016-17 in the research farm of ICAR-Indian Agricultural Research Institute (IARI), New Delhi, situated at a latitude of 28^{o}40’N and longitude of 77^{o}12’E, and an altitude of 228.6m above the mean sea level. The soil is sandy clay loamy with 7.5 pH, EC (0.32 dSm), OC (0.55%), available N-201 kg^{-1}, available P-12.8 kg^{-1} and available K-213.8 kg^{-1}.

Weather profile of the experimental site

The experimental site has a subtropical semi-arid environment with hot, dry summers and cold winters. It falls under the agro-climatic zone, of Trans-Gangetic plains’. May and June are the hottest months, with maximum temperatures ranging from 41 to 46 degrees Celsius, while temperatures start to drop from September onward. With minimum temperatures ranging from 5 to 7 degrees Celsius, January is the coldest month of the year. The average annual rainfall is 650 mm, with July to August becoming the wettest months. The average yearly evaporation is roughly 850 mm.

Treatments and experimental design

The two-year field trials were conducted with twelve treatments involving combinations of different doses, methods, sources and times of potassium application. The trial was conducted in a randomized block design and replicated thrice. The treatment details are presented in Table 1. During both the year, the wheat cv 'HD 2967' is sown in the mid of November using seed drill and harvested in the month of April with the row spacing of 0.22 m and seed rate of 100 kg/ha. The blanket dose of 120 kg nitrogen ha^{-1} was applied in 3 splits by applying $1/3^{rd}$ at 10 days after sowing (DAS), $1/3^{rd}$ at tillering (50 DAS) and the remaining $1/3^{rd}$ at spike initiation stage (80 DAS) through urea fertilizer. Similarly, the general recommended dose of 60 kg P_2O_5 ha^{-1} was applied through single super phosphate just before sowing and incorporated into the soil while sowing by seed drill. Potassium was applied according to the treatments. The foliar spray (FS) of 2.5% potassium nitrate was given at active tillering (45-50 DAS) followed by spike initiation (SI) stage (75-80 DAS) only in selected treatments (Table 1). The remaining all other agronomic management practices were carried out as per the standard recommendation.

Table 1: Treatment details

Trt no	Details	K_2O (Kg/ha)
T1	No application of K (control)	0
T2	Basal application of 60 kg K_2O/ha through muriate of potash (MOP)	60
T3	Basal application of 30 kg K_2O/ha through MOP	30
T4	Basal application of 30 kg K_2O/ha followed by 30 kg K_2O/ha at spike initiation (SI) through MOP	60
T5	Basal application of 45 kg K_2O/ha followed by 15 kg K_2O/ha at spike initiation (SI) through MOP	60
T6	2 foliar sprays (1^{st} active tillering, 2^{nd} SI) of 2.5% KNO_3	8.8
T7	Basal application of 60 kg K_2O/ha through MOP followed by 2 foliar sprays (1^{st} active tillering, 2^{nd} SI) of 2.5% KNO_3	68.8
T8	Basal application of 30 kg K_2O/ha through MOP followed by 2 foliar sprays (1^{st} active tillering, 2^{nd} SI) of 2.5% KNO_3	38.8
T9	Basal application of 45 kg K_2O/ha followed by 2 foliar sprays (1^{st} active tillering, 2^{nd} SI) of 2.5% KNO_3	53.8
T10	Basal application of 30 kg K_2O/ha plus 30 kg K_2O/ha at SI through MOP followed by 2 foliar sprays (1^{st} active tillering, 2^{nd} SI) of 2.5% KNO_3	68.8

T11	Basal application of 45 kg K_2O/ha plus 15 kg K_2O/ha at PI through MOP followed by 2 foliar sprays (1st active tillering, 2nd PI) of 2.5% KNO_3	68.8
T12	Basal application of 90 kg K_2O/ha through MOP	90

Note: MOP – Muriate of potash; K – Potassium; SI – Spike initiation; KNO_3 – Potassium nitrate

Fe, Zn and Cu analysis

The Zn, Cu and Fe concentrations in straw and grain of wheat crop were determined as per the procedure described by Prasad et al. [12]. The total uptake of Zn, Cu and Fe uptake in wheat were calculated by multiplying the grain and straw yields with their respective concentrations and expressed in g ha^{-1}.

$$\text{Total zinc uptake (g/ha)} = \frac{(SY \times ZnC_S)}{1000} + \frac{(GY \times ZnC_G)}{1000}$$

$$\text{Total iron uptake (g/ha)} = \frac{(SY \times FeC_S)}{1000} + \frac{(GY \times FeC_G)}{1000}$$

$$\text{Total copper uptake (g/ha)} = \frac{(SY \times CuC_S)}{1000} + \frac{(GY \times CuC_G)}{1000}$$

Where, SY - Straw Yield (kg ha^{-1}), GY - Grain Yield (kg ha^{-1}), ZnC_S-Zinc concentration in straw (ppm), ZnC_G-Zinc concentration in grain (ppm), FeC_S-Iron concentration in straw (ppm), FeC_G-Iron concentration in grain (ppm), CuC_S-Copper concentration in straw (ppm), CuC_G-Copper concentration in grain (ppm).

Nutrient harvest index

The nutrient harvest index of Fe, Zn and Cu was calculated using the following formula and expressed in terms of percentage.

$$\text{Zinc harvest index (ZnHI)} = \frac{Zn_g}{Zn_t} \times 100$$

$$\text{Iron harvest index (FeHI)} = \frac{Fe_g}{Fe_t} \times 100$$

$$\text{Copper harvest index (CuHI)} = \frac{Cu_g}{Cu_t} \times 100$$

Where, Zn_g = Total Zn uptake in grain (g), Zn_t = Total Zn uptake in whole plant (grain + straw) (g), Fe_g = Total Fe uptake in grain (g), Fe_t = Total Fe uptake in whole plant (grain + straw) (g), Cu_g = Total Cu uptake in grain (g), Cu_t = Total Cu uptake in whole plant (grain + straw) (g).

Statistical analysis

The Statistical Analysis System (SAS) software was used to do a one-way analysis of variance (ANOVA) on the acquired data. The F-test was used to decide the significant effects of the K fertilization on Fe, Zn, and Cu uptake in straw and grain and its harvest index and the least significant difference (LSD) was used to compare means. Correlation analysis was performed using the data analysis tool pack of MS Excel 2016.

RESULTS AND DISCUSSION

Micronutrient concentrations and their uptake in wheat

Zinc concentration, uptake and harvest index

The Zn concentration and its uptake by wheat were affected significantly by potassium application during both the years of study (Table 2). The highest Zn concentration (38-39 ppm) was recorded in T11 and it remained at par with other treatments except for T6 and T1. Results showed Zn concentration in rice grain decreased significantly with no application of K fertilizer. The significantly lowest Zn concentration in grain (34-35 ppm) was recorded in T1. The split and foliar application of K showed a non-significant effect on Zn concentration in rice. A similar trend was also recorded in straw Zn concentration i.e. higher in K fertilized plot and the lowest in T1 (no K application). Interestingly the grain Zn concentration is higher than straw Zn concentration at all the levels of K fertilization. It shows a major portion of Zn taken by rice crop is remobilized to grain. The total Zn uptake, grain Zn uptake and straw Zn uptake were higher in K fertilized plot due to higher Zn concentration. The higher grain yield in K fertilized treatments, in turn, increased grain and straw Zn uptake. The total Zn uptake in the wheat crop was found 276-396 g/ha and 274-384 g/ha during the first and second year of the experiment respectively. The total Zn uptake between 60 kg K_2O/ha and 90 kg K_2O/ha was found non-significant during both the years of experiment. It shows the basal application of a higher dose of K (90 kg K_2O/ha) is not beneficial to the wheat crops. The Zn harvest index (Zn HI) was found non-significant during the first year and significant during the second year (Fig 1). The higher Zn HI in the K fertilized plot reveals remobilization of Zn inside the plant from straw to grain. The Zn HI of the wheat crop is found between 52.3-55.5% and 53.9-57.4% during the first and second year of experiment respectively. It's evident from the results that more than 50% of the Zn taken by the wheat crop is transported to grain. Though K application was found to increase remobilization of Zn to grain, the split and foliar sprays of K showed a non-significant effect on remobilization of Zn to grain. This may be due to the synergistic interaction of K with Fe [13]. The correlation between grain K concentration and grain Zn concentration was found positive with r values of 0.60 and 0.68 during the first and second year of the experiment respectively (Table 5). Soil application of K has been increased the absorption and translocation of Zn in plant system [14]. The external supply of K at spike initiation stage increase the post-anthesis Zn uptake and remobilization of pre-anthesis straw Zn store to grains which in turn leads to rising grain Zn concentration. [15]. Alternatively, the availability of Zn is higher in slightly acidic pH. The basal application of KCl might have decreased the soil pH through an acid-forming effect near the root vicinity which in turn increased the solubility and uptake. K increased Zn availability by releasing more amount of Zn from soil exchangeable site, which resulted in increased Zn uptake and reduced Zn deficiency [16]. The uptake of applied Zn by plants increased as the availability of K increased. K improves Zn uptake via boosting mycorrhizal connection by stimulating the production of fungal spores. [17].

Iron concentration, uptake and harvest index

The Fe concentration and its uptake by wheat were affected significantly by potassium application during both the years of study (Table 3). The highest Fe concentration (110-115 ppm) was recorded in T7 and T11 and it remained at par with other treatments except for T1, T3 and T6. It is evident from the result that, the Fe concentration in wheat grain decreased significantly with no application of K fertilizer. The Fe concentration increased with the increasing rate of K application. Similarly, the split application of a recommended dose of K and foliar sprays of K, significantly increased Fe concentration in grain. The application of 60 kg K_2O/ha increased the Fe concentration in grain by 13.4 and 12.3% during the first and second year of experiment respectively. The significantly lowest Fe concentration in grain (89 ppm – 1st year, 97 ppm – second year) was recorded in T1 (no K application). Similar to grain Fe concentration, the straw Fe concentration increased with the increasing rate of K fertilization and the lowest straw Fe concentration was recorded in T1 (no K application). However, the split and foliar application of K showed a non-significant effect on straw Fe concentration in comparison to basal application of a recommended dose of K. In general, the straw Fe concentration was 2.5 times more than grain Fe concentration. Result clearly shows the synergistic effect of K fertilization on Fe uptake, translocation and remobilization of Fe from straw to grain.

The total Fe uptake, grain Fe uptake and straw Fe uptake were higher in K fertilized plot due to higher Fe concentration and grain yield. The basal application of 60 kg K_2O/ha and two split applications of 60 kg K_2O/ha showed a non-significant difference in total Fe uptake. Similarly, basal application of 90 and 60 kg K_2O/ha showed a non-significant difference in total Fe uptake. The Fe harvest index (Fe HI) was found significant during both the year experiment (Fig 2). The significantly higher Fe HI in T7 and T11 shows the beneficial effect of K foliar sprays on Fe remobilization from straw to grain. The Fe HI of the wheat crop is found between 21.2-26.5% and 21-25.3% during the first and second year of experiment respectively. It's evident from the results that only 1/4th of the Fe taken by the wheat crop is transported to grain. Thus, K application either through foliar spray or top dressing in the later stage of the crop will help in increasing the Fe concentration in the grain. The correlation between grain K concentration and grain Fe concentration was found positive with r values of 0.72 and 0.70 during the first and second year of the experiment respectively (Table 5).

Fe deficiency is one of the major yield-limiting factors, particularly in calcareous soils [18]. The increased Fe uptake might be due to acidifying effect of KCl since the availability was more in the pH of 6.5 and below. The finding was in accordance with the results of Awad-Allah and Elsokkary [19] they found K nutrition has the potential to stimulate Fe uptake of monocot and dicot plants and facilitate Fe bio-fortification in crops. An adequate supply of K alleviates Fe deficiency-induced chlorosis in plants [20] and ensure the efficient use of Fe and too high concentration of K will cause competition with iron [21]. K supplementation boosted phenolic compound secretion and pectin methylation level while decreasing pectin and hemicellulose content, enabling Fe reutilization from root cell walls [20]. Furthermore, K supplementation improved Fe reutilization from vacuoles by increasing AtNRAMP3 expression. Moreover, K supplementation increased the expression of numerous genes involved in long-distance Fe transport, including AtFRD3, AtYSL2, and AtNAS1, implying that adequate K supply can promote Fe transport from roots to leaves [20].

Copper concentration, uptake and harvest index

The Cu concentration in wheat grain and straw were found influenced significantly by the rates, methods and times of K application during both the years of study (Table 4). The Cu concentration in grain and straw was found to increase with increasing dose of K application till 60 kg/ha after which it remained non-significant. However, the split application of 60 kg K/ha showed a non-significant effect on Cu uptake both in grain and straw. The basal application of 30 kg K/ha followed by 2 foliar sprays of K at maximum tillering and spike initiation stage resulted in statistically at par grain and straw Cu concentration with two split applications of 60 kg K/ha. The straw Cu concentration of wheat was found almost double that of grain Cu concentration. Similar to grain Cu concentration, the highest straw Cu concentration (18.1 ppm-1st year, 18.3 ppm-2nd year) was recorded in T11 and it remained statistically at par with other treatments except for T1 and T6. Due to higher Cu and grain yield in K fertilized plot, the grain Cu uptake, straw Cu uptake and total Cu uptake was highest in K fertilized plot. The two split applications of 60 kg K/ha followed by two foliar sprays of 2.5% K (T10, T11) recorded the highest Cu uptake and remained at par with other treatments except for T1, T3 and T6. The Cu harvest index (Cu HI) of the wheat crop was found statistically significant only during the first year and it ranged between 27.5 to 31.3% (Fig 3). It is evident from the result that, K influence the translocation of Cu inside the plant and under optimum K fertilization, the Cu remobilization to grain is increased significantly. Even under ideal K fertilization, only 30% of the Cu uptake by the wheat crop is translocated to grain. A major portion of Cu (70%) is stored in straw. The two split applications of 60 kg K/ha significantly increased the Cu remobilization to grain by 5.7% compared to the basal application of 60 kg K/ha. However, the two split applications of 60 kg K/ha followed by two foliar sprays of 2.5% K showed a non-significant effect on Cu HI. The correlation between grain K concentration and grain Cu concentration was found positive with r values of 0.63 and 0.65 during the first and second year of the experiment respectively (Table 5). Thus, optimum K fertilization in wheat not only increase grain yield but also increases the concentration of Fe, Zn and Cu in grain. A similar result of increasing Cu utilization with the use of K fertilizer is also reported by Anonymous [22]. K interaction with Cu is less conspicuous in science fiction. In general K interaction with Cu is positive in cereal crops (Waddington et al., 1972).

Conclusion

In light of the foregoing results, it is inferred that optimum supply of K based on 4R nutrient stewardship based K fertilization is an effective strategy to increase Fe, Zn and Cu concentration in wheat grain. Optimum K supply favours the uptake and translocation of Fe, Zn and Cu in plants and ultimately enhances the grain quality. Agronomic bio-fortification of wheat crops with essential micronutrients through balanced K fertilization is an effective approach to overcome malnutrition or micronutrient deficiency which retards the growth and development of both crops and humans.

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Declarations

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Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Authors' contributions

Conceptualization of research, designing of the experiment (SV, DK); Contribution of experimental materials (DK, YSS, DKS); Preparation of manuscript (VK, DK, YSS, DKS); Execution of field/ lab experiments & data collection (VK, TV); Data analysis, preparation of table and figures (VK). All authors reviewed the manuscript.

Ethics approval

Not applicable

Conflict of interest

No potential conflict of interest was reported by the authors.

Consent to participate

Not applicable

Consent for publication

The necessary permission for publication is obtained from PME cell, IARI, New Delhi.

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Table 2. Effect of K application on zinc (Zn) concentration and uptake by wheat

Treatment	Zn concentration in grain (mg kg^{-1})		Zn concentration in straw (mg kg^{-1})		Zn uptake by grain (g ha^{-1})		Zn uptake by straw (g ha^{-1})		Total Zn uptake (g ha^{-1})	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
T1	34.2^{B}	35.0^{D}	22.7^{C}	21.9	147^{D}	150^{E}	129^{D}	124^{C}	276^{D}	274^{C}
T2	37.2^{A}	38.0^{AB}	26.2^{AB}	25.4	194^{B}	194^{C}	167^{AB}	163^{A}	360^{B}	357^{A}
T3	36.3^{AB}	36.6^{BCD}	25.6^{AB}	24.1	173^{C}	172^{D}	157^{BC}	147^{AB}	331^{C}	318^{B}
T4	37.8^{A}	38.5^{AB}	26.8^{A}	25.1	214^{A}	213^{A}	172^{AB}	160^{A}	385^{AB}	373^{A}
T5	37.7^{A}	38.3^{AB}	26.7^{A}	24.8	212^{A}	212^{AB}	170^{AB}	158^{A}	382^{AB}	370^{A}
T6	34.9^{B}	35.6^{CD}	24.2^{BC}	23.1	160^{CD}	161DE	143^{CD}	134^{BC}	302^{D}	295^{BC}
T7	38.0^{A}	38.4^{AB}	27.2^{A}	25.6	216^{A}	213^{A}	175^{AB}	164^{A}	391^{A}	377^{A}
T8	37.4^{A}	37.8^{ABC}	26.6^{AB}	24.8	194^{B}	194^{C}	166^{AB}	160^{A}	360^{B}	354^{A}
T9	37.6^{A}	38.0^{AB}	26.8^{A}	24.7	213^{A}	209^{ABC}	173^{AB}	158^{A}	386^{AB}	366^{A}
T10	37.5^{A}	39.1^{A}	26.5^{AB}	25.1	213^{A}	217^{A}	172^{AB}	162^{A}	385^{AB}	378^{A}
T11	38.3^{A}	39.7^{A}	27.3^{A}	25.5	218^{A}	220^{A}	178^{A}	164^{A}	396^{A}	384^{A}
T12	37.3^{A}	38.1^{AB}	26.3^{AB}	24.5	195^{B}	195^{BC}	168^{AB}	158^{A}	363^{B}	353^{A}
SE(d)	1.07	1.04	1.15	1.12	6.67	8.13	8.90	10.0	13.15	16.6
LSD (P=0.05)	2.22	2.15	2.38	NS	13.82	16.87	18.45	20.74	27.27	34.3

Note: T1 = No K (control), T2 = 60 kg K_2O/ha at basal, T3 = 30 kg K_2O/ha at basal, T4 = 30 kg K_2O/ha at basal + 30 kg K_2O/ha at spike initiation, T5 = 45 kg K_2O/ha at basal + 15 kg K_2O/ha at spike initiation, T6 = 2 foliar spray of 2.5% KNO_3, T7 = T2 + T6, T8 = T3 + T6, T9 = 45 kg K_2O/ha at basal + T6, T10 = T4 + T6, T11 = T5 + T6, T12 = 90 K_2O/ha at basal.

Table 3. Effect of K application on iron (Fe) concentration and uptake by wheat

Treatment	Fe concentration in grain (mg kg^{-1})		Fe concentration in straw (mg kg^{-1})		Fe uptake by grain (g ha^{-1})		Fe uptake by straw (g ha^{-1})		Total Fe uptake (g ha^{-1})	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
T1	89^{E}	97	249^{C}	275^{C}	381^{D}	413^{E}	1416^{D}	1558^{D}	1797^{E}	1971^{C}
T2	101^{CD}	109^{ABC}	263^{AB}	288^{AB}	522^{B}	555^{BC}	1672^{AB}	1849^{AB}	2194^{CD}	2404^{A}
T3	98^{D}	103^{CDE}	260^{AB}	284^{ABC}	466^{C}	485^{D}	1601^{BC}	1729^{BC}	2067^{D}	2214^{B}
T4	108^{ABC}	112^{AB}	266^{A}	291^{A}	607^{A}	619^{A}	1703^{AB}	1854^{AB}	2311^{ABC}	2473^{A}
T5	109^{ABC}	113^{AB}	267^{A}	292^{A}	610^{A}	621^{A}	1705^{AB}	1861^{AB}	2315^{ABC}	2482^{A}
T6	94DE	100DE	254^{BC}	280^{BC}	431^{CD}	452DE	1493^{CD}	1630^{CD}	1924^{E}	2081^{BC}
T7	110^{A}	115^{A}	270^{A}	292^{A}	625^{A}	631^{A}	1737^{AB}	1870^{A}	2361^{A}	2501^{A}
T8	101^{BCD}	107^{BCD}	265^{AB}	286^{AB}	524^{B}	548^{C}	1659^{AB}	1847^{AB}	2183^{CD}	2394^{A}
T9	109^{AB}	111^{AB}	267^{A}	288^{AB}	618^{A}	611^{AB}	1728^{AB}	1834^{AB}	2346^{AB}	2445^{A}
T10	108^{ABC}	114^{AB}	271^{A}	291^{A}	613^{A}	629^{A}	1755^{A}	1878^{A}	2369^{A}	2507^{A}
T11	110^{A}	115^{A}	271^{A}	292^{A}	627^{A}	636^{A}	1766^{A}	1878^{A}	2392^{A}	2514^{A}
T12	102^{ABCD}	110^{ABC}	265^{A}	288^{AB}	533^{B}	562^{BC}	1690^{AB}	1852^{AB}	2223^{BC}	2414^{A}
SE(d)	4.03	3.78	5.36	4.75	27.06	27.54	65.70	63.53	66.3	70.24
LSD (P=0.05)	8.35	7.83	11.11	9.86	56.12	57.12	136.26	131.75	137.5	145.67

Note: T1 = No K (control), T2 = 60 kg K_2O/ha at basal, T3 = 30 kg K_2O/ha at basal, T4 = 30 kg K_2O/ha at basal + 30 kg K_2O/ha at spike initiation, T5 = 45 kg K_2O/ha at basal + 15 kg K_2O/ha at spike initiation, T6 = 2 foliar spray of 2.5% KNO_3, T7 = T2 + T6, T8 = T3 + T6, T9 = 45 kg K_2O/ha at basal + T6, T10 = T4 + T6, T11 = T5 + T6, T12 = 90 K_2O/ha at basal.

Table 4. Effect of K application on copper (Cu) concentration and uptake by wheat

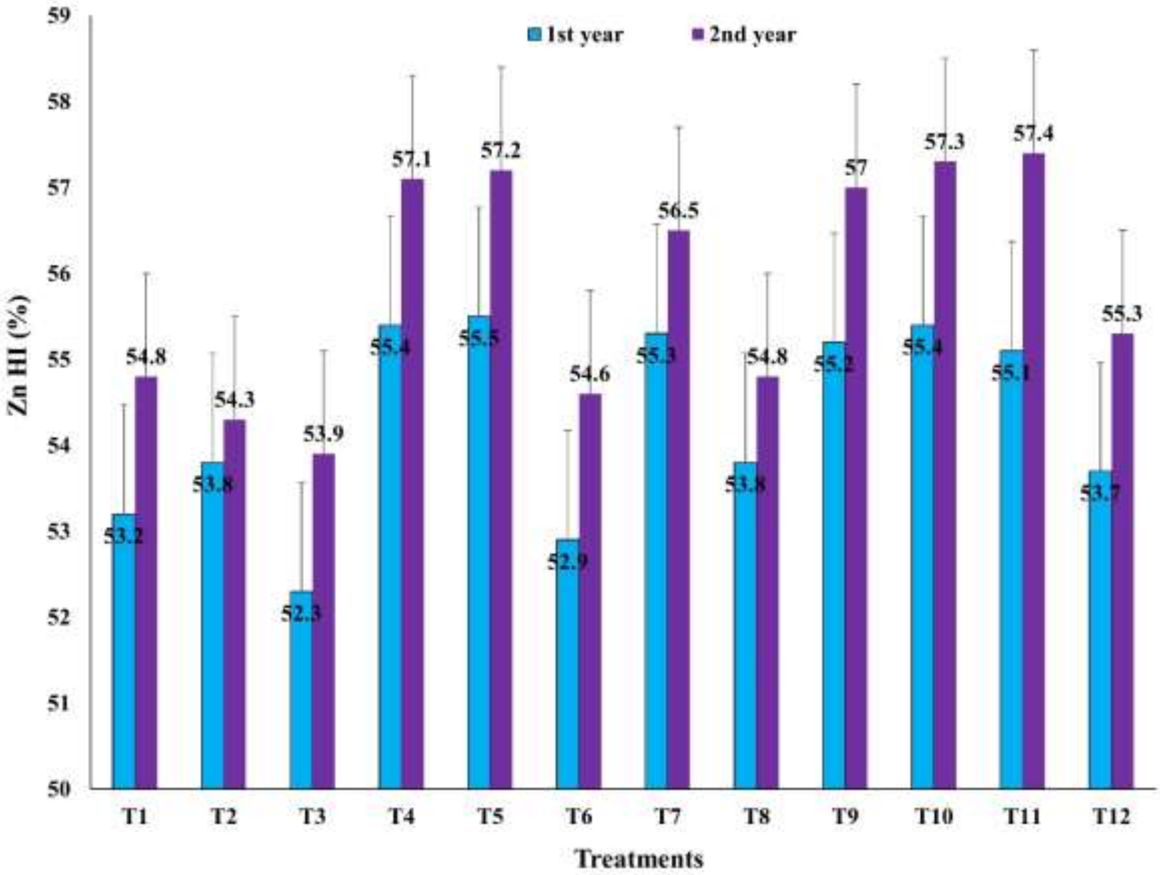
Treatment	Cu concentration in grain (mg kg^{-1})		Cu concentration in straw (mg kg^{-1})		Cu uptake by grain (g ha^{-1})		Cu uptake by straw (g ha^{-1})		Total Cu uptake (g ha^{-1})	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
T1	7.26^{C}	7.49^{C}	14.37^{C}	14.97^{D}	31.1^{E}	32.0^{D}	81.7^{D}	84.7^{D}	113^{D}	117^{C}
T2	8.65^{AB}	8.92^{A}	16.83^{AB}	17.43^{AB}	45.1^{BC}	45.5^{AB}	107.1^{AB}	111.9^{AB}	152^{AB}	157^{A}
T3	8.13^{ABC}	8.57^{AB}	16.10^{ABC}	16.68^{BC}	38.8^{CD}	40.3^{BC}	99.1^{BC}	101.5^{BC}	138^{BC}	142^{B}
T4	8.89^{A}	9.00^{A}	17.21^{AB}	17.79^{AB}	50.2^{AB}	49.8^{A}	110.3^{AB}	113.6^{A}	160^{A}	164^{A}
T5	8.92^{A}	9.13^{A}	17.26^{AB}	17.86^{AB}	50.2^{AB}	50.5^{A}	110.4^{AB}	113.8^{A}	161^{A}	164^{A}
T6	7.63^{BC}	8.00^{BC}	15.11^{BC}	15.72^{CD}	34.9^{DE}	36.1^{CD}	89.0^{CD}	91.4^{CD}	124^{CD}	128^{BC}
T7	9.06^{A}	9.19^{A}	17.93^{A}	18.13^{A}	51.4^{AB}	50.9^{A}	115.3^{A}	116.0^{A}	167^{A}	167^{A}
T8	8.73^{AB}	9.04^{A}	17.28^{A}	17.43^{AB}	45.5^{AB}	46.3^{AB}	108.3^{AB}	112.4^{AB}	154^{AB}	159^{A}
T9	9.10^{A}	9.10^{A}	18.01^{A}	18.21^{A}	51.6^{AB}	49.9^{A}	116.4^{A}	116.1^{A}	168^{A}	166^{A}
T10	8.96^{A}	9.20^{A}	17.94^{A}	18.14^{A}	50.8^{AB}	51.0^{A}	115.9^{A}	117.0^{A}	167^{A}	168^{A}
T11	9.16^{A}	9.13^{A}	18.14^{A}	18.34^{A}	52.2^{A}	50.8^{A}	118.1^{A}	117.7^{A}	170^{A}	169^{A}
T12	8.73^{AB}	9.03^{A}	17.29^{A}	17.87^{AB}	45.4^{BC}	46.3^{AB}	110.1^{AB}	115.1^{A}	156^{AB}	161^{A}
SE(d)	0.55	0.40	1.04	0.63	3.24	2.95	7.60	5.53	10.49	7.44
LSD (P=0.05)	1.14	0.84	2.15	1.30	6.73	6.11	15.75	11.46	21.75	15.43

Note: T1 = No K (control), T2 = 60 kg K_2O/ha at basal, T3 = 30 kg K_2O/ha at basal, T4 = 30 kg K_2O/ha at basal + 30 kg K_2O/ha at spike initiation, T5 = 45 kg K_2O/ha at basal + 15 kg K_2O/ha at spike initiation, T6 = 2 foliar spray of 2.5% KNO_3, T7 = T2 + T6, T8 = T3 + T6, T9 = 45 kg K_2O/ha at basal + T6, T10 = T4 + T6, T11 = T5 + T6, T12 = 90 K_2O/ha at basal.

Table 5: Correlation between cationic micro-nutrient concentration in grain and straw

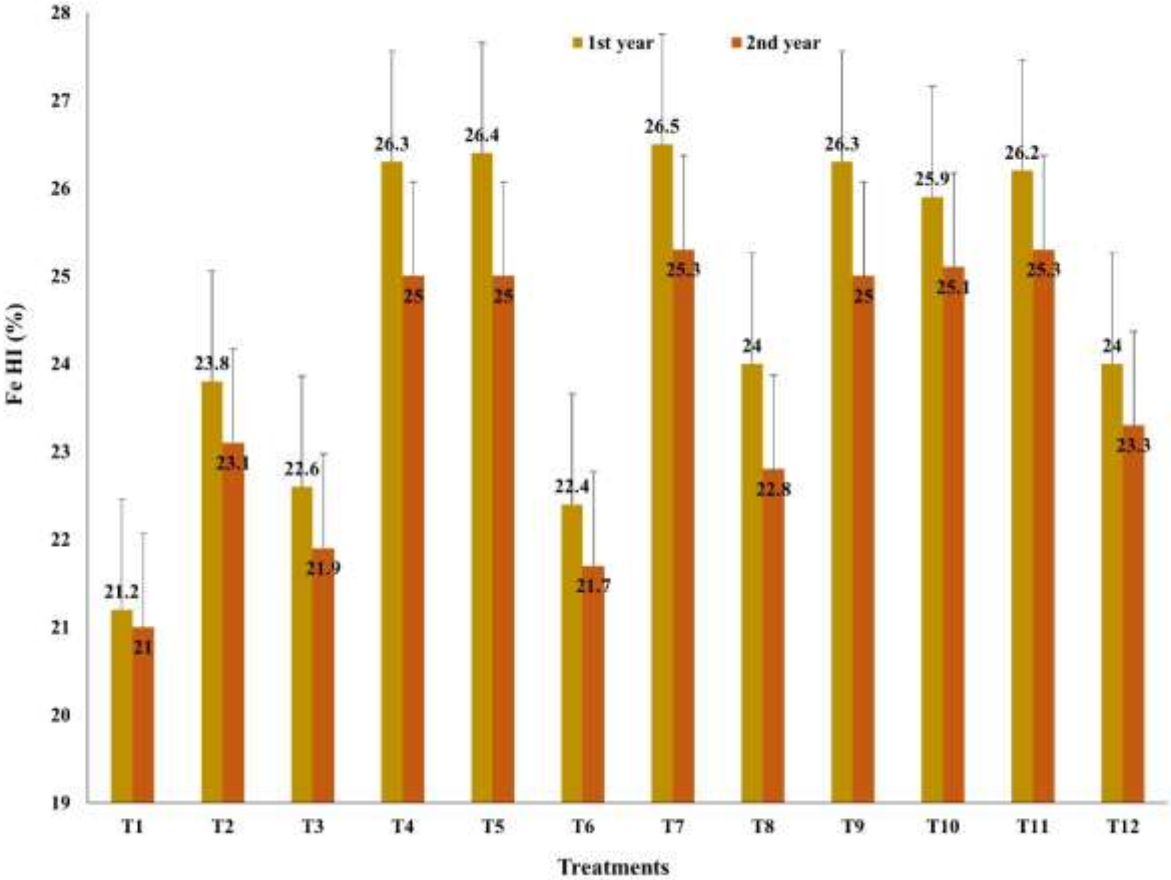
First year	Straw K_C	Straw Zn_C	Straw Fe_C	Straw Cu_C	Grain K_C	Grain Zn_C	Grain Fe_C	Grain Cu_C
Straw K_C	1.00							
Straw Zn_C	0.67	1.00						
Straw Fe_C	0.63	0.58	1.00					
Straw Cu_C	0.64	0.57	0.66	1.00				
Grain K_C	**0.88**	0.59	0.66	0.65	1.00			
Grain Zn_C	**0.60**	0.93	0.59	0.53	**0.55**	1.00		
Grain Fe_C	**0.72**	0.55	0.52	0.53	**0.79**	0.57	1.00	
Grain Cu_C	**0.63**	0.58	0.66	0.98	**0.62**	0.55	0.52	1.00
Second year								
Straw K_C	1.00							
Straw Zn_C	0.57	1.00						
Straw Fe_C	0.52	0.43	1.00					
Straw Cu_C	0.73	0.57	0.60	1.00				
Grain K_C	**0.87**	0.53	0.57	0.72	1.00			
Grain Zn_C	**0.68**	0.90	0.42	0.66	**0.63**	1.00		
Grain Fe_C	**0.70**	0.48	0.44	0.63	**0.77**	0.60	1.00	
Grain Cu_C	**0.65**	0.49	0.51	0.86	**0.65**	0.57	0.59	1.00

Fig 1. Potassium fertilization effect on Zn HI



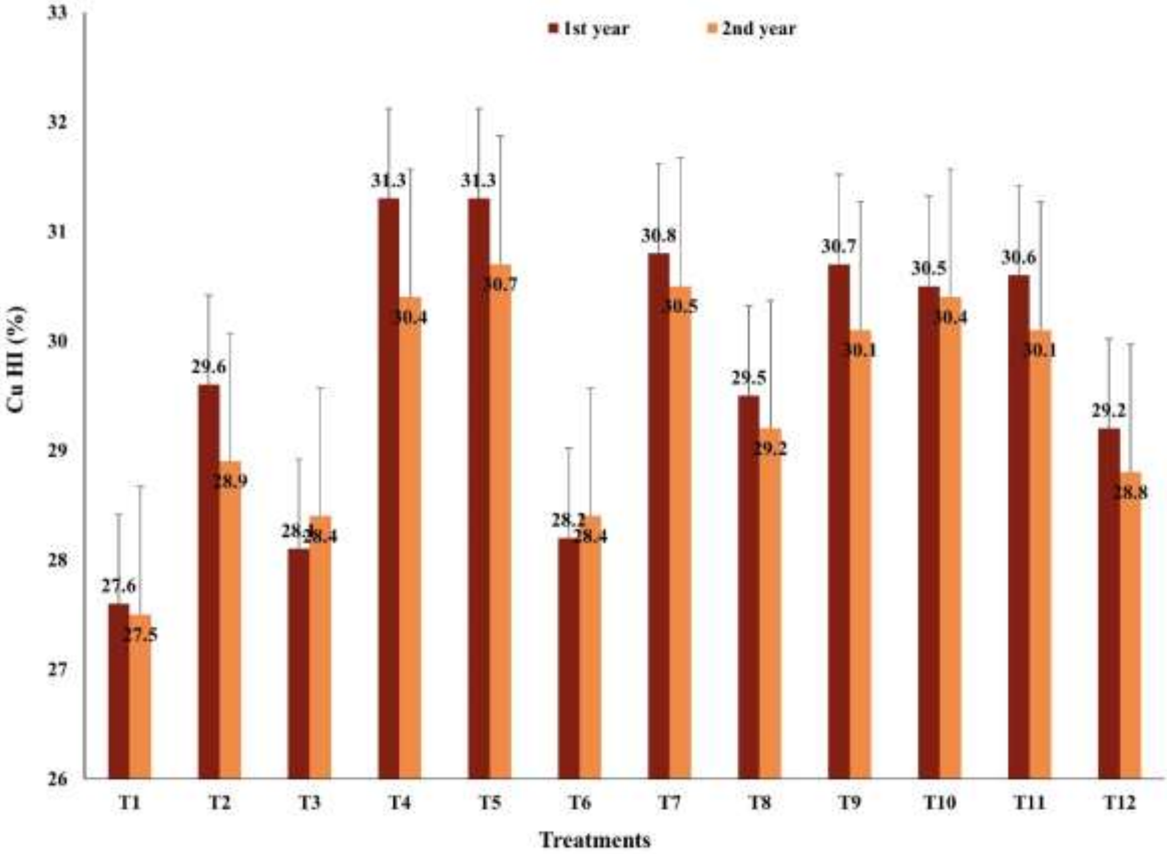
Note: T1 = No K (control), T2 = 60 kg K_2O/ha at basal, T3 = 30 kg K_2O/ha at basal, T4 = 30 kg K_2O/ha at basal + 30 kg K_2O/ha at spike initiation, T5 = 45 kg K_2O/ha at basal + 15 kg K_2O/ha at spike initiation, T6 = 2 foliar spray of 2.5% KNO_3, T7 = T2 + T6, T8 = T3 + T6, T9 = 45 kg K_2O/ha at basal + T6, T10 = T4 + T6, T11 = T5 + T6, T12 = 90 K_2O/ha at basal.

Fig 2. Potassium fertilization effect on Fe HI



Note: T1 = No K (control), T2 = 60 kg K_2O/ha at basal, T3 = 30 kg K_2O/ha at basal, T4 = 30 kg K_2O/ha at basal + 30 kg K_2O/ha at spike initiation, T5 = 45 kg K_2O/ha at basal + 15 kg K_2O/ha at spike initiation, T6 = 2 foliar spray of 2.5% KNO_3, T7 = T2 + T6, T8 = T3 + T6, T9 = 45 kg K_2O/ha at basal + T6, T10 = T4 + T6, T11 = T5 + T6, T12 = 90 K_2O/ha at basal.

Fig 3. Potassium fertilization effect on Cu HI



Note: T1 **=** No K (control), T2 = 60 kg K_2O/ha at basal, T3 = 30 kg K_2O/ha at basal, T4 = 30 kg K_2O/ha at basal + 30 kg K_2O/ha at spike initiation, T5 = 45 kg K_2O/ha at basal + 15 kg K_2O/ha at spike initiation, T6 = 2 foliar spray of 2.5% KNO_3, T7 = T2 + T6, T8 = T3 + T6, T9 = 45 kg K_2O/ha at basal + T6, T10 = T4 + T6, T11 = T5 + T6, T12 = 90 K_2O/ha at basal.