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RESEARCH ARTICLE

Iron toxicity in lowland rice influenced by application of high potassic fertilizer with suitable cultivars enhanced productivity and climate resilience

Jevelin Swain[1*], Rajendra Kumar Panda[1], Rabindra Kumar Nayak[2] & Manoranjan Satapathy[3]

[1] Department of plant physiology, College of agriculture, OUAT, Bhubaneswar, Odisha, India
[2] Department of soil science, College of agriculture, OUAT, Bhubaneswar, Odisha, India
[3]Department of Agronomy, College of agriculture, OUAT, Bhubaneswar, Odisha, India
Odisha University of Agriculture and Technology, College of Agriculture, Bhubaneswar, Odisha, India-751 003

*Email: jevelinswain1997@gmail.com

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Abstract

Iron poisoning in low-land rice in India develops gradually and is primarily caused by anaerobic conditions in submerged rice fields. A high concentration of ferrous ions in the soil solution disrupts the potassium balance in rice plants, leading to adverse effects on crop growth. In the 2021–2022 period, an experiment was conducted in non-saline, iron-rich soil (pH –4.82, Fe–458.6 mg kg^{-1}) to mitigate iron toxicity in rice cultivars through potassium nutrition. The experiment involved 4 potassium application doses (K-40, K-80, K-100 and K-120) and 32 rice cultivars, replicated twice using a split-plot design. Higher potassium doses led to increased tiller counts, but gradually decreased root length. Notably, cultivars like Kanchan, Indravati, Jagabandhu, Santepheap and Salibahan exhibited the lowest iron concentration in their grains compared to susceptible cultivars. Administering K-120 resulted in a yield increase of over 36.70 q ha^{-1}. Grain yield increased with higher K dosage, although it did not affect total iron content. However, K doses did influence specific fractions of iron in the soil. Hence, potassium nutrition appears crucial in managing iron toxicity in inceptisols, especially when paired with cultivars tolerant to iron toxicity.

Keywords

rice cultivars; potassium nutrition; iron toxicity; total iron; exchangeable iron

Introduction

Rice serves as a fundamental food source for nearly half of the world's population, providing essential calories. To sustainably feed an estimated 9.1 billion people by 2050, an additional 100 million tonnes of rice production is required (1). However, despite favorable conditions, the genetic potential for rice grain yield has plateaued, leading to decreased productivity. Abiotic stressors such as soil toxicity, salinity, acidity and nutrient deficiencies significantly impede grain yield across all rice-growing environments (2). Consequently, considerable efforts are directed towards developing rice varieties resilient to iron-poisoned soil. The physiological response of rice plants to low-lying soil profoundly influences their ability to tolerate high iron concentrations. The rhizosphere, where roots interact with soil, exhibits higher oxidation levels compared to the surrounding growing media. This is facilitated by rice roots transporting molecular oxygen into the root medium through air chambers and aerenchyma present in leaves, stems, nodes and roots. Moreover, ferrous iron in the soil solution oxidizes to Fe (III), forming visible deposits on the surface of rice roots. Rice roots exhibit greater oxidizing capacity at growth points and elongating portions compared to basal regions. Iron uptake for rice plants primarily occurs from the soil, necessitating readily available ferrous ions for healthy growth and development. However, excessive iron in the soil disrupts several physiological processes in the rhizosphere, contributing to iron poisoning affecting approximately 18 % of global soil. Elevated iron concentrations in toxic environments can range from 200 to 1000 ppm. To mitigate iron toxicity, rice cultivars accumulate excess iron in vacuoles and apoplasts, facilitating detoxification through reactive oxygen species production and the activation of antioxidant enzymes.

Rice roots possess various mechanisms to combat iron toxicity, including their ability to repel iron at the root surface, thereby preventing its uptake into the roots. Potassium has been implicated in both iron exclusion at the root level and its subsequent translocation from roots to shoots, indicating its crucial role in iron toxicity mitigation (3, 4). When plants receive an adequate supply of potassium, the enhanced redox potential becomes more apparent. As iron concentrations decrease and bronzing intensity diminishes, there is an increase in potassium concentration and accumulation in rice shoots. This dilution effect amplifies dry matter production. Consequently, efforts have been directed towards integrating rice cultivars resilient to iron toxicity with effective potassium management strategies. This endeavor aims to generate insights that can enhance rice yields in low-lying soil environments afflicted with iron toxicity.

Materials and Methods

Plant materials

Thirty-two well-known rice cultivars (Moti, Bina Dhan 11, Urvashi, Kanchan, Ramachandi, Jagannath, Indravati, Jagabandhu, Hasant, Swarna, Tejaswini, Pratikshya, Tanmayee, Manaswini, Hiranmayee, Upahar, Habira, MTU-1010, IR-64, Ranidhan, Santepheap, Kalakrushna, Rambha, Mahalaxmi, Ashutosh, Lalat, Manika, Mahanadi, Salibahan, Savitri, Prachi, Mrunalini) were sourced from the Department of Genetics and Plant Breeding, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha (Supplementary Table 1).

Experimental site

The current field experiment was conducted at the Central Experimental Farm of the Odisha University of Agriculture and Technology, located in Bhubaneswar, Odisha, India (200 15' N latitude, 850 52' E longitude, elevation 25.9 m above mean sea level), during the wet season of 2021 and 2022. This area falls within the east and southeastern coastal plain agroclimatic zone of Odisha and the east coastal plain and Hills zone of humid tropical India. The experimental plot featured sandy loam soil with a pH of 4.82 and an organic carbon content of 0.54 % (Table 1).

Supplementary Table 1. Details of plant materials

Sl no	Name	Duration (days)	Source of released
1	Moti	145	NRRI, CUTTACK
2	Bina Dhan 11	135	Bangladesh
3	Urbashi	145	OUAT
4	Kanchan	155	OUAT
5	Ramachandi	155	OUAT
6	Jagannath	150	OUAT
7	Indravati	150	OUAT
8	Jagabandhu	150	OUAT
9	Hasanta	145	OUAT
10	Swarna	145	ANGRAU
11	Tejaswini	135	OUAT
12	Pratikshya	140-145	OUAT
13	Tanmayee	150	OUAT
14	Manaswini	125-130	OUAT
15	Hiranmayee	135	OUAT
16	Upahar	160	OUAT
17	Habira	145	Local
18	MTU-1010	130	ANGRAU
19	IR 64	125	IRRI
20	Ranidhan	145	OUAT
21	Santepheap	150-155	Cambodia
22	Kalakrushna	135	Local
23	Rambha	155	OUAT
24	Mahalaxmi	155	OUAT
25	Ashutosh	150	OUAT
26	Lalat	125	OUAT
27	Manika	155	OUAT
28	Mahanadi	150	OUAT
29	Salibahan	155	DRR, HYDERABAD
30	Savitri	160	NRRI, CUTTACK
31	Prachi	155	OUAT
32	Mrunalini	145-150	OUAT

Table 1. Initial and post-harvest soil properties

Condition	Treatments	pH	EC (dS m^{-1})	OC	DTPA-Fe (mg kg^{-1})	DTPA-Mn (mg kg^{-1})	DTPA-Zn
Initial soil		4.82	0.051	5.40	458.6	-	-
Post-harvest soil	**K-40**	4.63	0.155	1.65	94.86	1.28	1.11
	K-80	4.57	0.189	3.60	93.14	1.17	1.16
	K-100	4.83	0.116	5.65	107.5	1.47	1.68
	K-120	4.73	0.202	7.70	97.0	2.08	1.77

This soil type was classified as a medium fertile, non-saline (EC-0.051dS m^{-1}) inceptisol, characterized by deep and inadequately drained properties. Additionally, it exhibited low accessibility to nitrogen, phosphorus and potassium, with respective levels of N, P_2O5. K_2O recorded at 172.6, 10.8 and 58.5 kg ha^{-1}. The experiment spanned 160 days, during which various climatic parameters were monitored. Daytime temperatures averaged 35.2 °C, while night time temperatures averaged 23.2 °C. Relative humidity levels were recorded at 92 % and 72.5 % at 7 AM and 2 PM respectively, with an average of 4.3 h of bright sunshine per day. The region experienced a yearly rainfall of 1628 mm, with approximately 80 % occurring between June and October over 70 to 80 rainy days. This area is characterized by a hot, humid subtropical climate, facilitating crop growth for 180 days or more annually.

Experimental details

The experiment was designed using a split-plot layout, featuring 32 common rice varieties assigned to the main plots and 4 potassium treatment levels (control with K_2O at 40 kg ha^{-1}, K_2O at 80 kg ha^{-1}, K_2O at 100 kg ha^{-1} and K_2O at 120 kg ha^{-1}) assigned to the subplots. Each treatment was replicated twice. Although mid-season draining of the field is an effective management strategy for iron toxicity, this particular field had poor drainage facilities.

Plant, Soil sampling and analysis

After harvesting the crop, rice grains from different cultivars were collected and prepared for Fe and K analyses. The grains were ground into a fine powder. For the analysis, 0.5 g of the powdered samples were placed in 5 mL of concentrated nitric acid for pre-digestion overnight. Subsequently, the samples were digested in a diacid mixture (3:2 HNO_3: $HClO_4$). The digested solution was filtered and made up to a volume of 50 mL. The Fe content was analyzed using an Atomic Absorption Spectrometer (AAS), while K was measured using a flame photometer.

To determine the DTPA-extractable Fe, 20 mL of DTPA was added to 10 g of soil and shaken for 2 h using a mechanical shaker. The solution was then filtered and the Fe content was measured using AAS. Sequential fractionation of Fe was performed using polypropylene centrifuge tubes containing 5 g of sieved soil (5). Since the extraction process is sequential, careful attention was required at each stage to extract a specific fraction without losing any soil. This meticulous process was maintained throughout the extraction. The following procedure was used to extract each chemical fraction:

Exchangeable Fe- After adding 25 mL of 1 M NH_4NO_3 at a pH of 7.0 to a 5 g soil sample in a centrifuge tube, the mixture was agitated for 2 h using a mechanical shaker. The sample was then centrifuged for 10 min at 1776 rpm and the supernatant was filtered for analysis. The residue was retained for extraction of the second fraction.

Carbonate bound Fe- The residue was then combined with 25 mL of 1M sodium acetate adjusted to pH 5.0 with acetic acid and shaken for 5 h. After the shaking process, the suspension was centrifuged and the supernatant filtered for examination.

Iron/manganese oxides bound Fe- The residue from the previous step was treated for 5 h in a water bath with 50 mL of 0.04M NH_2OHHCl in 25 % acetic acid. After allowing the mixture to settle, it was centrifuged and filtered for analysis. The residue was then retained for further examination.

Organic matter bound Fe- The residue was treated with 5 mL of 30 % H_2O_2 and 3 mL of 0.02 M HNO_3 and then placed in a water bath for 3 h. After cooling, 50 mL of NH_4NO_3 was added and the mixture was shaken for 2 h. Subsequently, it was filtered, centrifuged and analyzed.

Residual Fe- After drying and crushing the residue, the organic Fe was removed. A 50 mL Teflon beaker was filled with 1.0–0.5 g of soil. To this, 5 mL of hydrofluoric acid, 1 mL of perchloric acid and a few drops of concentrated H_2SO_4 were added. The mixture was then heated on hot plates until the soil completely dissolved. This procedure was repeated as necessary. The dissolved material was then transferred to a 100 mL volumetric flask, filtered and analyzed.

$$\text{1.Exchangeable Fe} \left(\frac{\text{mg}}{\text{kg}}\right) = \text{Fe concentration x } \frac{\text{Solution (ml)}}{\text{Soil (g)}}$$

$$\text{2.Carbonate bound Fe} \left(\frac{\text{mg}}{\text{kg}}\right) = \text{Fe concentration x } \frac{\text{Solution (ml)}}{\text{Soil (g)}} \text{ x Dilution factor}$$

$$\text{3.Fe \& Mn oxide bound Fe} \left(\frac{\text{mg}}{\text{kg}}\right) = \text{Fe concentration x } \frac{\text{Solution (ml)}}{\text{Soil (g)}} \text{ x Dilution factor}$$

$$\text{4.Organic matter bound Fe} \left(\frac{\text{mg}}{\text{kg}}\right) = \text{Fe concentration x } \frac{\text{Solution (ml)}}{\text{Soil (g)}} \text{ x Dilution factor}$$

$$\text{5.Residual Fe} \left(\frac{\text{mg}}{\text{kg}}\right) = \text{Fe concentration x } \frac{\text{Solution (ml)}}{\text{Soil (g)}} \text{ x Dilution factor}$$

The experiment detailed in this publication was conducted during the Kharif seasons of 2021 and 2022. Consistent trends and outcomes were observed each year. Although absolute levels varied due to seasonal effects, the responses to different cultivars and soil management strategies remained consistent. The data presented here represents the experiment from the 2022 season.

Statistical analysis

The data were analysed statistically using a split-plot design (6, 7). Statistical analysis, correlation coefficients and scatter diagram were generated uisng Microsoft Office Excel 2019. Cluster analysis of the rice cultivars was performed using R Software (R.4.3.0) (8).

Results

Effect on tiller number, root length and SPAD value at maximum tillering stage

In all 32 rice cultivars, the number of tillers per plant increased with potassium nutrition from 40 kg to 120 kg K_2O ha^{-1} at the maximum tillering stage. The plants treated with 120 kg K_2O ha^{-1} exhibited the highest tiller count among the cultivars and this increase was found to be significant for both the cultivars and the potassium treatment doses. There was also a statistically significant interaction between the potassium applications rates and the variations among cultivars. The lowest tiller number was observed in all cultivars treated with 40 kg K_2O ha^{-1} and this difference was also significant. Similarly, root length at the maximum tillering stage was measured, revealing that iron toxicity influences root growth.

However, root growth was more significantly impacted at 120 kg K_2O ha^{-1} than at 40 kg K_2O ha^{-1}, except in the cases of Kanchan, Mahalaxmi and Savitri, where the lowest root growth was observed at 40 kg K_2O ha^{-1}. The dosages, variety and interaction of the roots were crucial. Similarly, the chlorophyll concentration, expressed in SPAD values as an indicator of nitrogen content, showed a gradual increase with the increased application of K_2O. This increase was significant for most cultivars, except for Urbasi, Hasant, Mahalaxmi, Manika, Ashutosh, Mahanadi, Salibahan and Savitri, where the SPAD values increased significantly as potassium application increased from 40 to 120 K_2O ha^{-1} (Table 2).

Table 2. Effect of potassium doses on tiller no. and root length and SPAD value of rice cultivars grown under iron toxic soil at maximum tillering stage

Sl. No.	Cultivars	Tiller number				Root length				SPAD			
		K-40	K-80	K-100	K-120	K-40	K-80	K-100	K-120	K-40	K-80	K-100	K-120
1	Moti	6.0	7.0	8.0	8.0	22.00	13.00	14.00	13.50	17.20	7.00	10.20	14.20
2	Bina Dhan 11	8.0	10.0	10.0	19.0	19.50	9.50	20.00	12.50	10.13	5.58	4.27	11.60
3	Urbashi	7.0	9.0	13.0	13.0	16.50	9.00	12.50	17.50	6.59	6.15	12.10	14.60
4	Kanchan	11.0	13.0	14.0	15.0	19.00	19.00	12.00	22.00	15.80	9.85	9.15	12.80
5	Ramachandi	8.0	10.0	10.0	11.0	24.00	15.50	19.00	16.50	9.42	6.89	7.74	8.78
6	Jagannath	11.0	13.0	16.0	16.0	19.00	16.00	16.00	20.50	17.40	8.63	10.90	16.20
7	Indravati	9.0	9.0	10.0	13.0	15.00	13.00	16.00	14.50	11.48	6.24	16.40	8.65
8	Jagabandhu	6.0	7.0	8.0	13.0	28.00	14.50	20.00	16.00	5.97	7.57	8.64	7.67
9	Hasanta	7.0	8.0	8.0	11.0	22.00	14.00	19.00	14.50	11.62	6.60	11.00	7.80
10	Swarna	11.0	11.0	11.0	12.0	23.00	19.00	21.50	13.50	7.60	11.90	5.11	12.21
11	Tejaswini	5.0	5.0	6.0	14.0	18.00	10.00	20.00	12.00	10.64	5.24	10.20	9.52
12	Pratikshya	7.0	7.0	8.0	11.0	18.00	11.00	11.00	14.00	8.28	3.97	17.70	4.98
13	Tanmayee	10.0	10.0	10.0	11.0	24.00	12.00	12.00	15.00	7.68	6.02	18.40	7.04
14	Manaswini	11.0	11.0	12.0	12.0	23.50	10.00	21.50	12.00	9.80	8.48	8.39	8.68
15	Hiranmayee	7.0	7.0	7.0	9.0	21.50	11.00	13.00	15.00	8.21	6.55	13.20	8.00
16	Upahar	7.0	10.0	11.0	12.0	21.00	18.00	20.00	16.60	6.46	3.51	4.23	3.86
17	Habira	5.0	5.0	6.0	11.0	21.00	14.50	18.50	15.50	13.84	4.06	10.00	5.02
18	MTU-1010	6.0	6.0	7.0	7.0	22.50	10.00	20.00	11.00	11.37	4.17	4.25	4.24
19	IR 64	9.0	12.0	13.0	14.0	22.00	21.00	21.00	16.50	9.72	8.76	5.55	9.42
20	Ranidhan	12.0	13.0	13.0	13.0	25.00	14.00	22.00	15.50	8.06	3.28	8.31	4.64
21	Santepheap	8.0	9.0	9.0	16.0	24.50	15.00	16.00	15.50	12.00	8.49	6.12	8.69
22	Kalakrushna	8.0	11.0	17.0	17.0	25.00	17.00	21.00	22.50	14.80	5.75	10.90	4.74
23	Rambha	10.0	10.0	15.0	17.0	22.50	17.00	12.00	16.50	12.10	6.05	5.50	7.56
24	Mahalaxmi	14.0	14.0	15.0	16.0	12.50	13.00	14.00	22.50	10.60	7.44	21.00	14.70
25	Ashutosh	10.0	11.0	12.0	14.0	21.00	15.00	15.00	15.50	7.94	14.40	8.81	15.40
26	Lalat	6.0	7.0	8.0	8.0	23.00	8.00	13.50	14.00	15.40	9.21	3.02	8.60
27	Manika	9.0	12.0	16.0	19.0	25.00	9.00	15.00	12.00	15.70	10.50	4.00	24.20
28	Mahanadi	5.0	7.0	10.0	12.0	21.00	15.00	7.00	17.00	8.34	6.95	8.04	13.41
29	Salibahan	9.0	9.0	12.0	13.0	24.50	17.50	16.00	12.50	9.80	7.68	11.10	11.90
30	Savitri	9.0	10.0	10.0	13.0	14.00	13.50	12.00	17.00	3.20	5.92	3.40	14.80
31	Prachi	8.0	8.0	9.0	10.0	23.00	14.00	12.00	15.50	8.68	6.83	17.10	7.84
32	Mrunalini	11.0	13.0	13.0	14.0	24.00	17.50	23.00	16.50	9.52	6.59	6.12	7.94
	Mean	8.4	9.5	10.8	12.9	21.39	13.92	16.42	15.66	10.48	7.07	9.40	9.99
		D	V	V within D	D within V	D	V	V within D	D within V	D	V	V within D	D within V
	SEM (±)	0.36	0.08	0.65	0.66	0.001	0.000	0.002	0.002	0.0015	0.0004	0.0028	0.0029
	C.D. (0.05)	1.04	0.23	1.81	1.88	0.002	0.001	0.004	0.004	0.0044	0.0010	0.0080	0.0082
	CV %	9.74	8.75			0.012	0.013			0.047	0.044		

Effect on iron and potassium content in rice grain

The iron concentration in grain was significantly impacted by treatment, cultivar diversity and their interaction. Potassium treatments resulted in a progressive decrease in iron concentration, from 40 kg K_2O to 120 kg K_2O ha^{-1}. Cultivars such as Kanchan, Indravati, Jagabandhu, Santepheap and Salibahan exhibited lower iron contents at 120 kg K_2O ha^{-1} compared to other cultivars. Additionally, the potassium concentration in the grain increased in all cultivars across treatments ranging from K-40 to K-120 and this increase was found to be significant. Indravati Swarna, MTU-1010 and Mahanadi had higher K concentrations, ranging from 0.31 to 0.37 %, compared to other cultivars (Supplementary Table 2).

Effect on grain yield and straw yield

The grain yields of all cultivars increased with potassium application, with K-120 resulting in larger yields compared to the other treatments. Although grain output was lowest in K-40, it was observed that grain yield was significantly influenced by the 4 potassium treatment doses, cultivar diversity and their interaction. The highest grain yield, measured in kg K_2O ha^{-1}, was observed in Indravati (45 q ha $^{-1}$), followed by Mahanadi, Manika, Tejaswini and Upahar with yield ranging between 42 and 43 q ha^{-1}. Conversely, straw yield exhibited the opposite trend, with varieties treated with K-40 showing maximum production, except for Kanchan, Urbasi, Upahar, MTU-1010 and Savitri. Additionally, it was demonstrated that straw yield was affected by the treatments, the varieties and their interactions.

Supplementary table-2 Effect of potassium doses on iron concentration (ppm) and potassium concentration (%) in grains of rice cultivars grown under iron toxic soil

Sl no	Cultivars	Iron concentration (ppm)				K concentration (%)			
		K-40	K-80	K-100	K-120	K-40	K-80	K-100	K-120
1	Moti	125.50	108.30	69.10	58.70	0.20	0.22	0.25	0.28
2	Bina Dhan 11	141.80	106.80	104.10	72.70	0.17	0.21	0.23	0.28
3	Urbashi	133.80	110.70	92.10	72.60	0.16	0.25	0.27	0.27
4	Kanchan	138.00	100.60	49.10	33.10	0.16	0.21	0.22	0.26
5	Ramachandi	134.90	118.40	102.30	78.60	0.18	0.22	0.22	0.25
6	Jagannath	114.70	101.80	89.00	83.90	0.18	0.22	0.24	0.27
7	Indravati	111.10	93.50	86.30	67.11	0.20	0.24	0.32	0.37
8	Jagabandhu	186.30	114.20	102.00	48.20	0.20	0.20	0.21	0.24
9	Hasanta	122.70	89.10	46.30	33.50	0.16	0.20	0.23	0.25
10	Swarna	144.30	109.00	67.30	36.30	0.22	0.26	0.32	0.35
11	Tejaswini	121.40	76.10	44.80	30.60	0.19	0.21	0.24	0.27
12	Pratikshya	156.70	132.10	122.40	51.70	0.22	0.23	0.24	0.25
13	Tanmayee	193.00	102.30	91.70	54.70	0.22	0.23	0.27	0.30
14	Manaswini	159.30	133.50	132.50	121.00	0.17	0.22	0.23	0.24
15	Hiranmayee	111.10	89.20	86.10	38.00	0.19	0.22	0.27	0.29
16	Upahar	186.50	154.20	117.90	88.40	0.19	0.21	0.23	0.29
17	Habira	142.20	119.00	81.50	43.30	0.18	0.22	0.25	0.28
18	MTU-1010	146.40	136.20	80.40	45.50	0.17	0.24	0.30	0.32
19	IR 64	130.00	112.30	85.80	56.50	0.19	0.21	0.23	0.26
20	Ranidhan	120.40	90.80	74.60	55.20	0.19	0.24	0.27	0.27
21	Santepheap	134.40	114.50	103.90	43.40	0.18	0.21	0.24	0.27
22	Kalakrushna	101.50	84.90	78.70	50.60	0.23	0.28	0.33	0.37
23	Rambha	157.60	117.40	92.20	87.00	0.18	0.23	0.24	0.27
24	Mahalaxmi	141.80	120.90	75.20	38.30	0.18	0.22	0.24	0.28
25	Ashutosh	129.20	125.60	103.10	46.60	0.19	0.23	0.26	0.30
26	Lalat	136.00	103.90	75.10	70.90	0.20	0.20	0.23	0.30
27	Manika	162.10	132.60	108.80	83.80	0.18	0.21	0.23	0.24
28	Mahanadi	145.70	115.80	42.00	36.00	0.19	0.24	0.27	0.31
29	Salibahan	114.80	98.00	81.20	66.10	0.17	0.20	0.24	0.26
30	Savitri	129.65	94.80	51.50	47.30	0.17	0.20	0.23	0.28
31	Prachi	158.50	123.90	104.30	48.00	0.20	0.22	0.22	0.24
32	Mrunalini	129.40	122.10	80.40	72.00	0.17	0.22	0.23	0.27
	Mean	139.40	111.02	85.05	58.11	0.18	0.22	0.25	0.28
		D	V	V within D	D within V	D	V	V within D	D within V
	SEm (±)	0.48	0.12	0.95	0.95	0.004	0.001	0.009	0.009
	C.D. (0.05)	1.40	0.33	2.66	2.69	0.010	0.003	0.025	0.024
	CV %	1.39	1.36			4.361	5.524		

Effect on Harvest index

The potassium treatments produced mixed results regarding the harvest index, which was determined to be noteworthy. Among the cultivar, Santepheap displayed a particularly strong harvest index in response to potassium treatments (Table 3).

Correlation coefficient

The results were further confirmed by Karl Pearson's Correlation analysis, which showed a strong positive correlation ($p < 0.01$) between grain yield and the uptake of both iron and potassium. Similarly, straw yield also correlated with the uptake of iron and potassium at different doses of potassic fertilizer (Table 4).

Table 3. Effect of potassium doses on grain yield and Straw yield and harvest index of rice cultivars grown under iron toxic soil

Sl. No.	Cultivars	Grain yield (q ha^{-1})				Straw yield (q ha^{-1})				Harvest Index (%)			
		K-40	K-80	K-100	K-120	K-40	K-80	K-100	K-120	K-40	K-80	K-100	K-120
1	Moti	26.75	28.50	27.50	28.50	52.20	43.20	36.00	36.90	33.88	39.75	43.31	43.58
2	Bina Dhan 11	33.75	33.25	30.00	37.50	39.60	35.10	34.20	45.00	46.01	48.65	46.73	45.45
3	Urbashi	32.25	31.50	29.25	33.00	58.50	45.00	55.80	67.50	35.54	41.18	34.39	32.84
4	Kanchan	30.00	36.00	38.00	39.00	52.20	56.70	61.20	64.80	36.50	38.83	38.31	37.57
5	Ramachandi	15.00	39.00	36.00	40.50	34.20	43.20	46.80	48.60	30.49	47.45	43.48	45.45
6	Jagannath	30.00	30.00	31.50	33.00	34.20	47.70	52.20	36.00	46.73	38.61	37.63	47.83
7	Indravati	27.00	29.25	41.25	45.00	32.40	54.00	56.70	54.00	45.45	35.14	42.11	45.45
8	Jagabandhu	30.75	31.50	30.00	36.00	45.00	46.80	43.20	54.00	40.59	40.23	40.98	40.00
9	Hasanta	27.75	30.00	31.50	33.00	37.80	40.50	43.20	44.10	42.33	42.55	42.17	42.80
10	Swarna	32.25	31.50	34.50	37.50	36.90	36.00	38.70	45.00	46.64	46.67	47.13	45.45
11	Tejaswini	33.00	33.00	33.75	42.00	34.40	35.10	38.20	44.20	48.96	48.46	46.91	48.72
12	Pratikshya	27.75	27.00	30.00	30.75	45.90	44.10	42.30	42.30	37.68	37.97	41.49	42.09
13	Tanmayee	39.00	30.00	33.25	39.00	54.90	36.00	37.40	41.50	41.53	45.45	47.06	48.45
14	Manaswini	35.25	32.25	32.25	38.25	43.20	37.80	38.60	43.20	44.93	46.04	45.52	46.96
15	Hiranmayee	24.50	28.50	25.50	29.25	45.90	31.50	29.70	36.90	34.80	47.50	46.20	44.22
16	Upahar	22.50	30.00	40.50	42.00	38.70	40.50	54.90	58.50	36.76	42.55	42.45	41.79
17	Habira	26.00	24.00	24.75	37.50	43.20	32.40	31.50	45.90	37.57	42.55	44.00	44.96
18	MTU-1010	27.00	27.75	37.50	41.25	36.00	37.80	43.20	48.60	42.86	42.33	46.47	45.91
19	IR 64	28.50	29.25	35.25	39.00	31.50	36.00	39.00	41.00	47.50	44.83	47.47	48.75
20	Ranidhan	24.75	29.25	30.00	30.75	43.20	38.70	45.00	43.20	36.42	43.05	40.00	41.58
21	Santepheap	21.00	26.25	36.00	38.25	30.60	45.00	43.20	45.00	40.70	36.84	45.45	45.95
22	Kalakrushna	25.50	27.00	27.00	29.25	68.34	44.38	63.90	55.03	27.17	37.83	29.70	34.71
23	Rambha	37.50	36.00	30.00	37.50	49.50	63.00	58.50	61.20	43.10	36.36	33.90	37.99
24	Mahalaxmi	32.25	28.50	25.50	37.50	43.20	36.00	39.60	48.60	42.74	44.19	39.17	43.55
25	Ashutosh	31.50	37.50	36.00	37.50	36.00	43.20	54.00	45.00	46.67	46.47	40.00	45.45
26	Lalat	28.50	28.50	29.25	33.75	30.60	32.50	33.30	45.00	48.22	46.72	46.76	42.86
27	Manika	37.50	40.50	30.75	42.00	45.00	54.00	47.70	48.60	47.60	42.86	39.20	46.36
28	Mahanadi	36.00	37.50	36.25	43.50	38.50	47.70	43.20	47.50	48.32	44.01	45.63	47.80
29	Salibahan	28.50	26.25	22.50	34.50	38.70	53.10	49.50	52.20	42.41	33.08	31.25	39.79
30	Savitri	33.00	27.00	23.25	36.00	55.80	45.00	64.80	71.10	37.16	37.50	26.41	33.61
31	Prachi	37.50	28.50	26.25	37.50	55.80	37.80	40.50	47.70	40.19	42.99	39.33	44.01
32	Mrunalini	27.00	24.00	33.00	34.50	34.00	36.00	52.20	39.60	44.26	40.00	38.73	46.56
	Mean	29.67	30.59	31.50	36.70	42.69	42.37	45.57	48.37	41.30	42.14	41.23	43.39
		D	V	V within D	D within V	D	V	V within D	D within V	D	V	V within D	D within V
	SEM (±)	0.008	0.002	0.016	0.016	0.77	0.19	1.55	1.55	0.45	0.11	0.89	0.89
	C.D. (0.05)	0.022	0.006	0.046	0.045	2.23	0.54	4.34	4.37	1.29	0.31	2.50	2.52
	CV %	0.066	0.072			4.89	4.89			3.01	3.00		

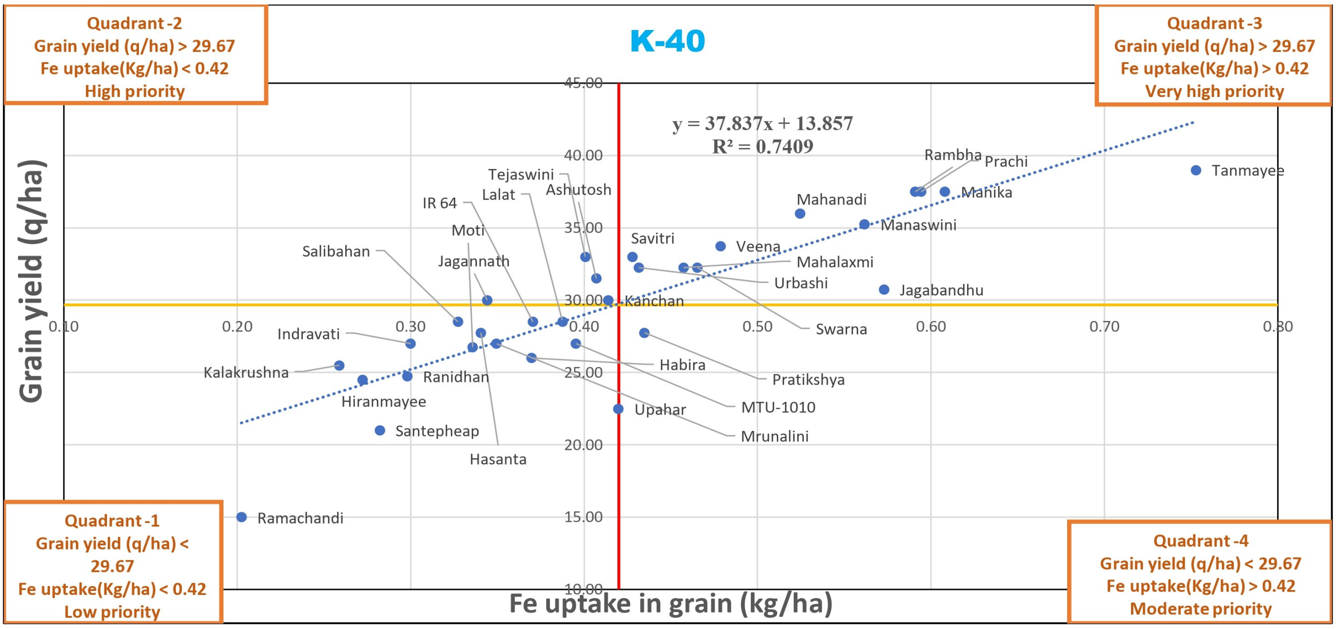
Table 4. Simple correlation analysis

	K-40GY	K-80 GY	K-100 GY	K-120 GY	K-40SY	K-80 SY	K-100 SY	K-120 SY	K-40 Fe uptake	K-80 Fe uptake	K-100 Fe uptake	K-120 Fe uptake	K-40 K uptake	K-80 K uptake	K-100 K uptake
K-80 GY	0.291														
K-100 GY	-0.188	0.381													
K-120 GY	0.208	0.445	**0.631***												
K-40SY	0.322	-0.048	-0.482	-0.397											
K-80 SY	0.151	0.417	0.149	0.178	0.184										
K-100 SY	-0.022	0.153	0.179	0.073	0.315	**0.690****									
K-120 SY	0.125	0.166	-0.012	0.222	0.442	**0.530***	**0.711****								
K-40 Fe uptake	**0.861****	0.311	-0.034	0.322	0.300	0.095	-0.121	0.122							
K-80 Fe uptake	0.205	**0.741****	0.404	0.493	-0.112	0.288	0.089	0.122	0.424						
K-100 Fe uptake	-0.176	0.186	**0.516***	0.311	-0.243	0.054	0.041	-0.089	0.134	**0.579***					
K-120 Fe uptake	0.085	0.300	0.255	0.352	-0.164	0.239	0.171	0.097	0.226	**0.542***	**0.672****				
K-40 K uptake	**0.869****	0.195	-0.125	0.127	0.342	0.040	-0.127	-0.055	**0.810****	0.109	-0.092	-0.029			
K-80 K uptake	0.257	**0.852****	0.402	0.334	0.130	0.358	0.233	0.163	0.237	**0.612***	0.174	0.197	0.289		
K-100 K uptake	-0.132	0.175	**0.813****	0.477	-0.283	0.095	0.185	-0.010	-0.108	0.129	0.317	0.068	0.033	0.461	
K-120 K uptake	0.076	0.166	**0.604***	**0.734****	-0.272	0.095	0.162	0.187	0.067	0.148	0.162	0.122	0.168	0.361	**0.809****

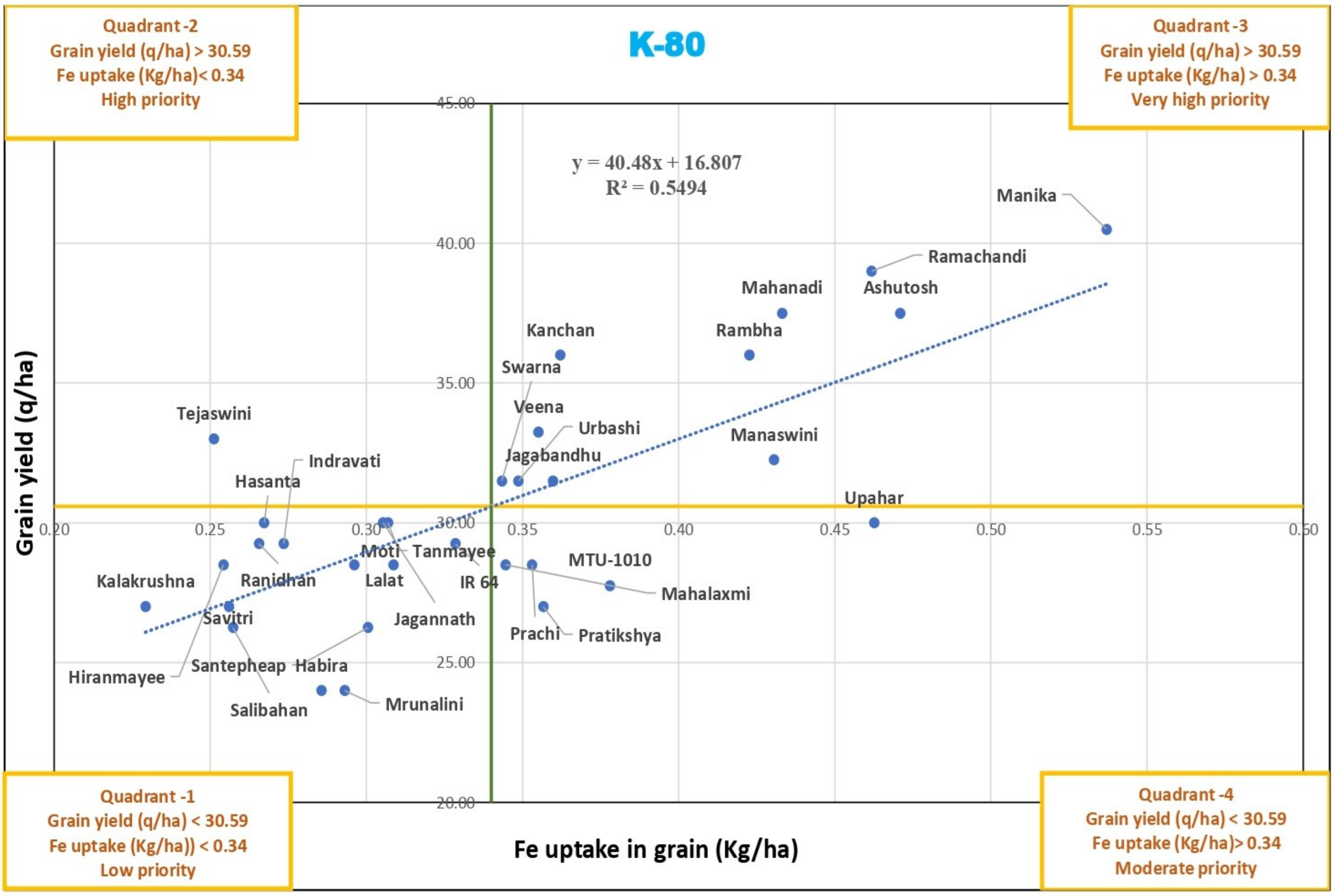
**** signifies correlated at p value of 0.01, * signifies correlated at p value of 0.05**

Screening of cultivars based on grain yield, iron and potassium content

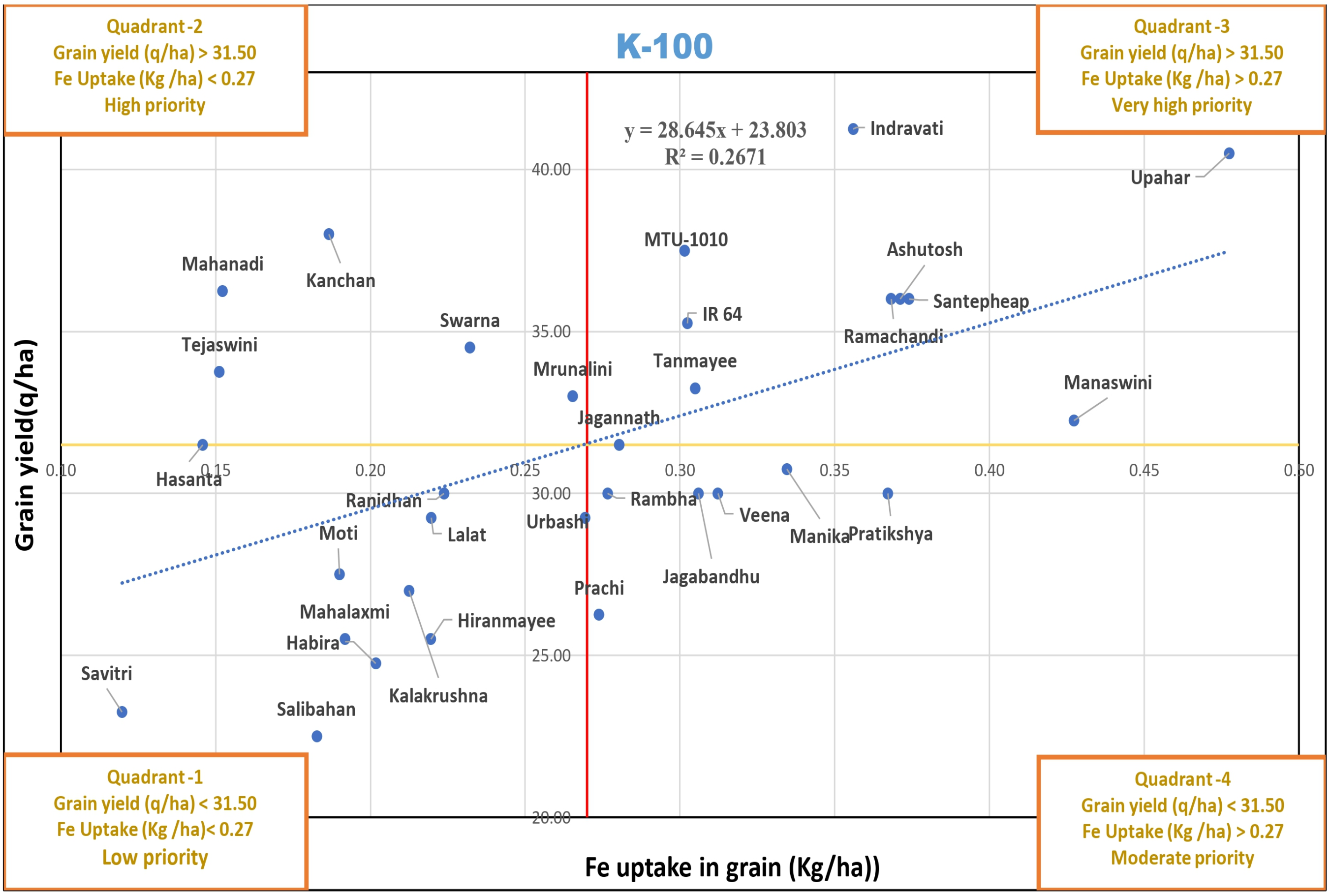
The scatter diagram analysis of the relationship between grain yield and iron uptake (Supplementary Figs. 1-4) revealed that nine rice cultivars in quadrant 3, classified as the very high priority group, yielded more than 36.07 q ha^{-1} when treated with the maximum potassium levels. Similarly, the scatter diagram analysis of the association between potassium uptake and grain yield (Supplementary Figs. 5-8) showed that 12 cultivars in quadrant 3, categorized as the extremely high priority group, absorbed more than 10.27 kg ha^{-1} of potassium. Among these, the Indravati, Upahar, Tanmayee and Bina rice cultivars exhibited similarities in their uptake of Fe and K concerning grain yield under optimal potassium nutrition (K-120).



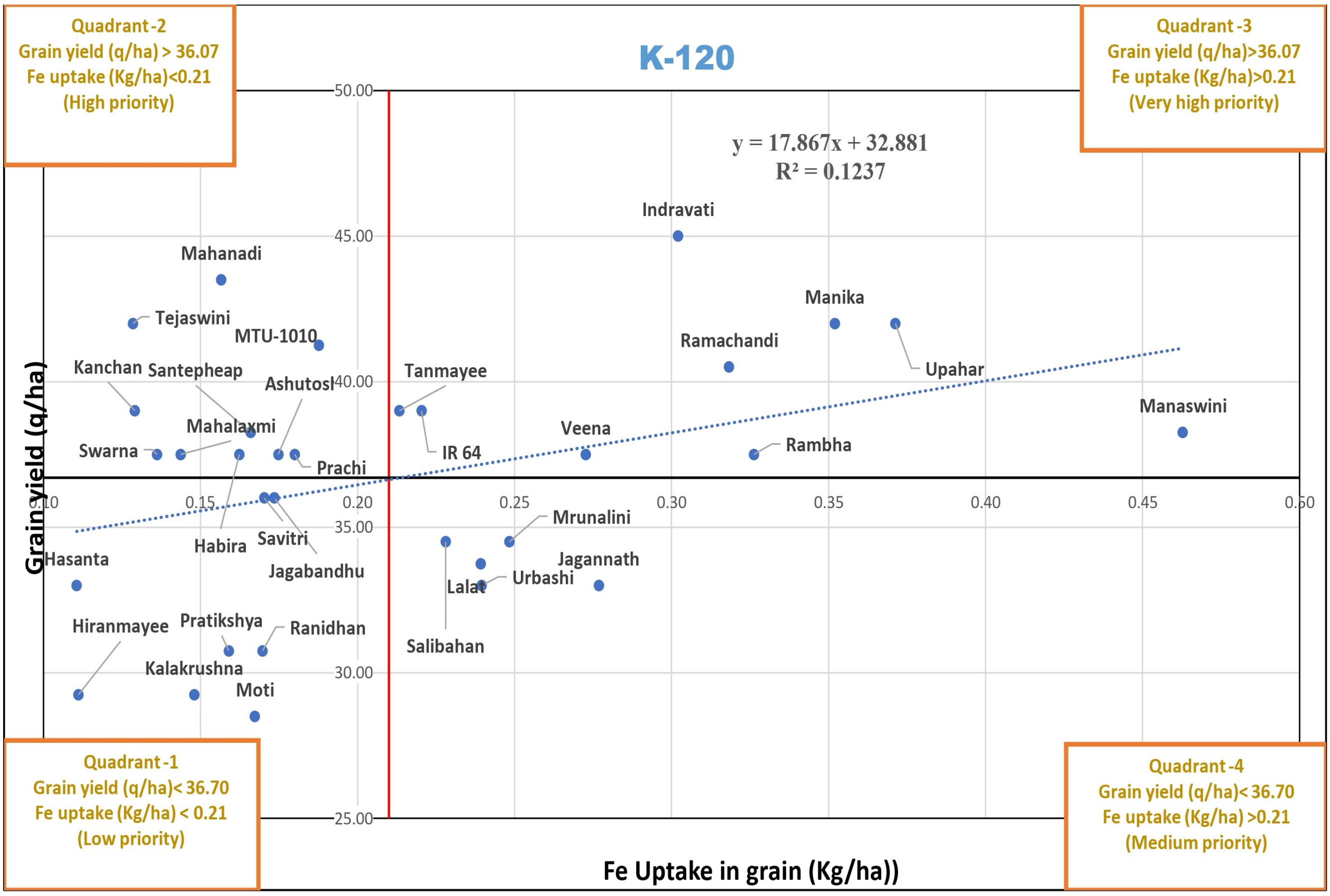
Supplementary Fig. 1. Scatter Diagram (Relationship between grain yield and iron uptake in grain of treatment K-40).



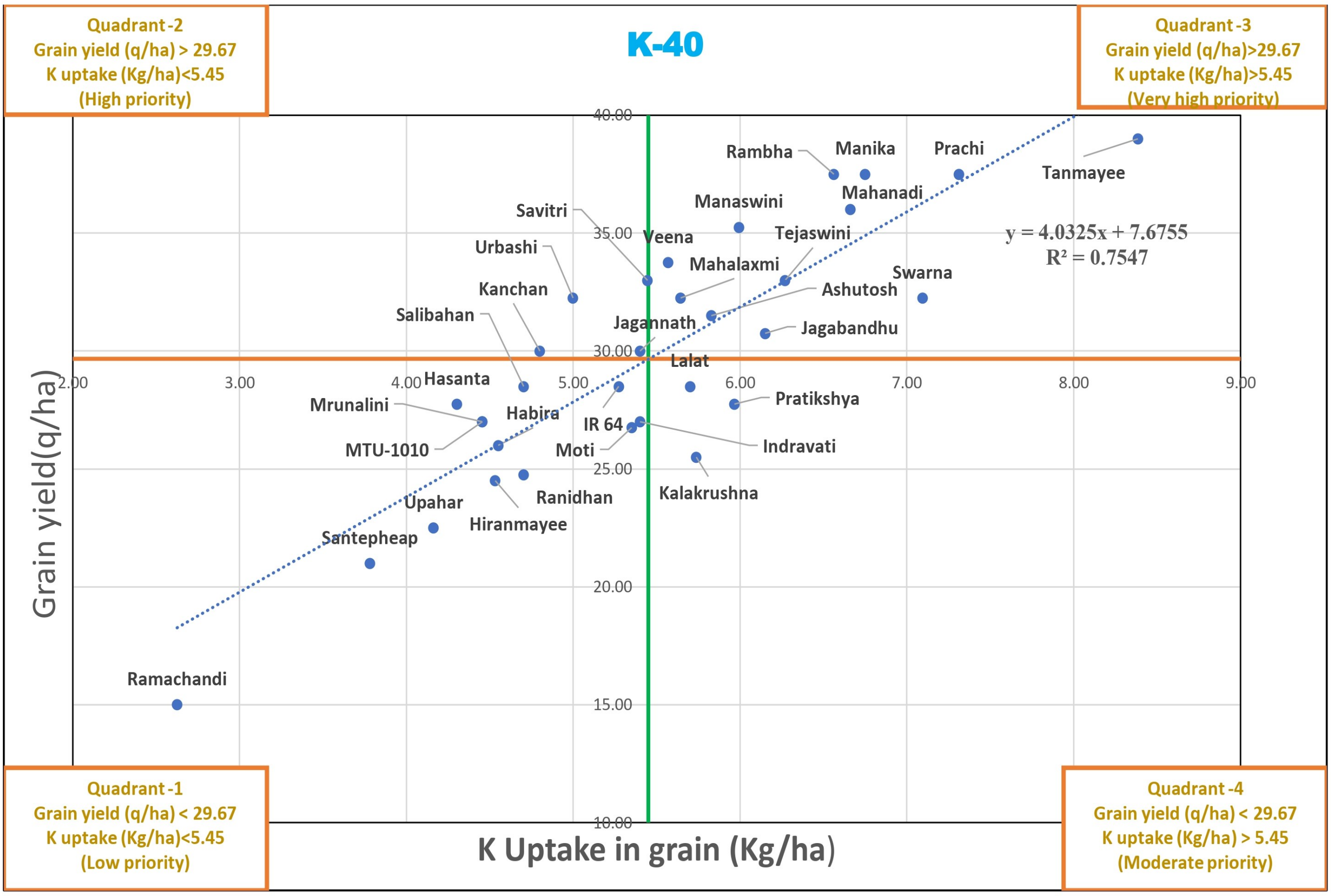
Supplementary Fig. 2. Scatter Diagram (Relationship between grain yield and iron uptake in grain of treatment K-80).



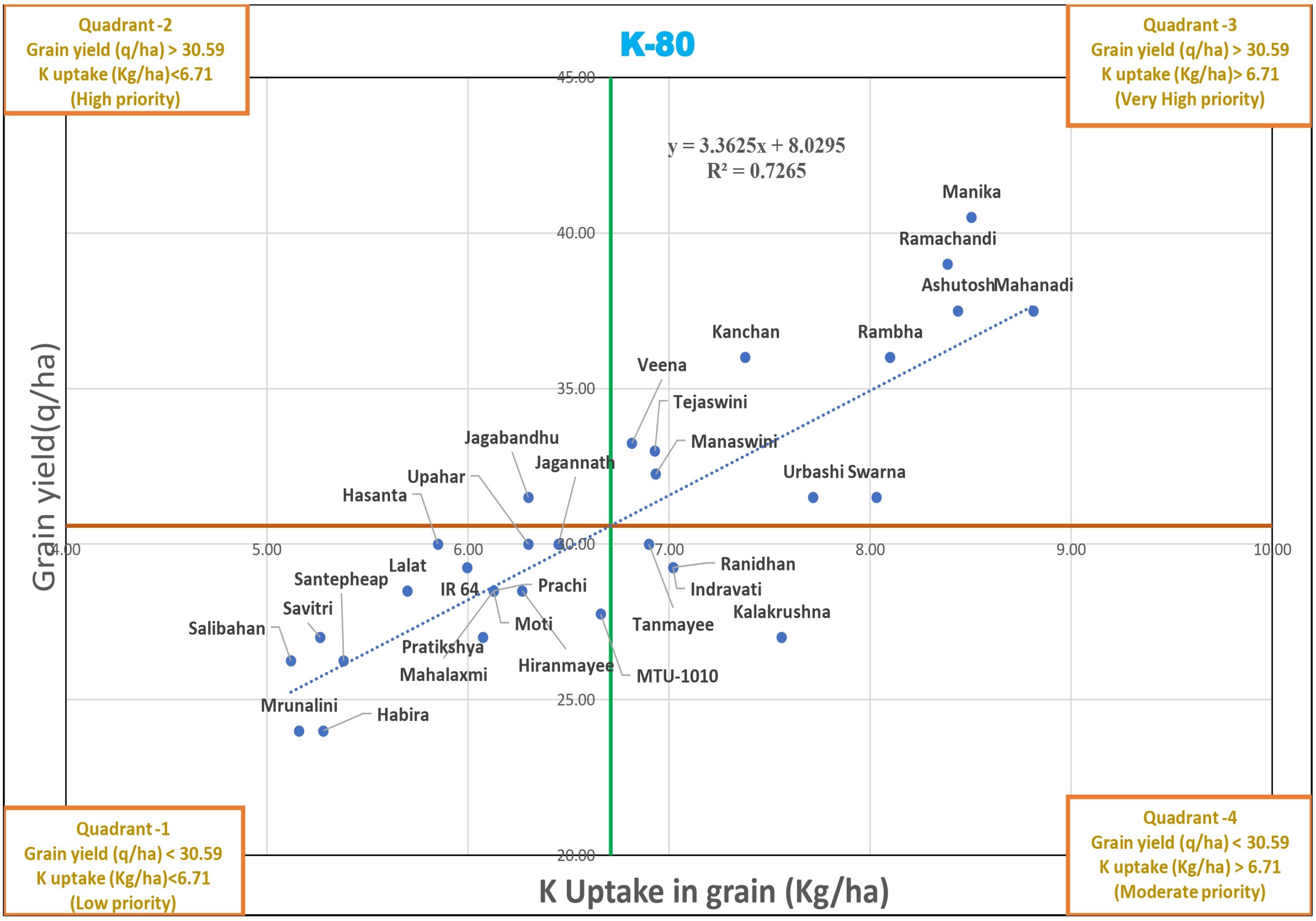
Supplementary Fig. 3. Scatter Diagram (Relationship between grain yield and iron uptake in grain of treatment K-100).



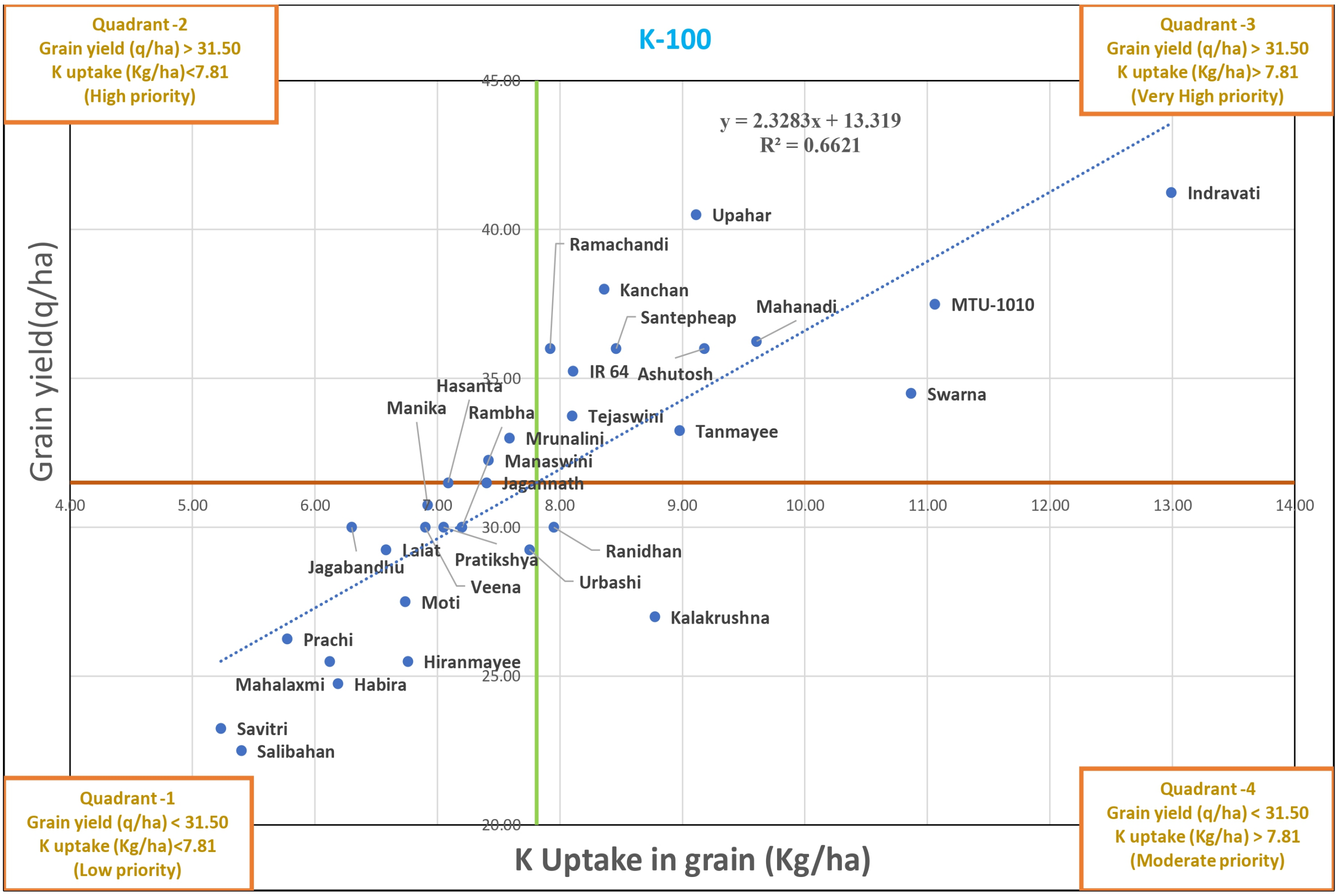
Supplementary Fig. 4. Scatter Diagram (Relationship between grain yield and iron uptake in grain of treatment K-120).



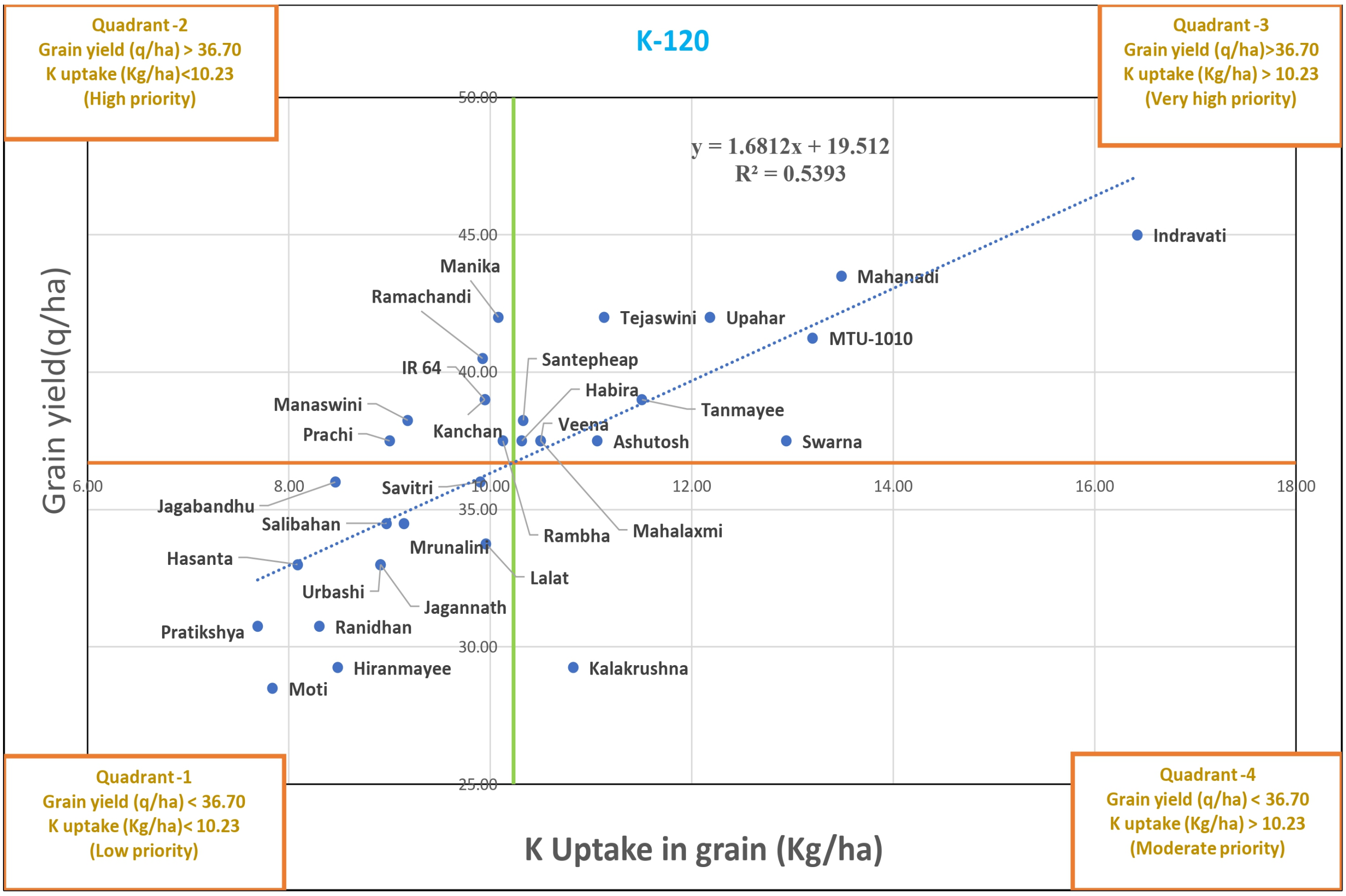
Supplementary Fig. 5. Scatter Diagram (Relationship between grain yield and potassium uptake in grain of treatment K-40).



Supplementary Fig. 6. Scatter Diagram (Relationship between grain yield and potassium uptake in grain of treatment K-80).



Supplementary Fig. 7. Scatter Diagram (Relationship between grain yield and potassium uptake in grain of treatment K-100).



Supplementary Fig. 8. Scatter Diagram (Relationship between grain yield and potassium uptake in grain of treatment K-120).

Further cluster analysis, based on grain/straw yield, harvest index, iron/potassium content and uptake, was conducted using R software and identified 2 naturally occurring data clusters (Fig. 1). Within these clusters, cultivars such as Indravati, Santepheap and Kanchan demonstrated high performance, followed by Salibahan with moderate ability. Conversely, Jagabandhu exhibited susceptibility in iron-toxic soil treated with potassium nutrition.

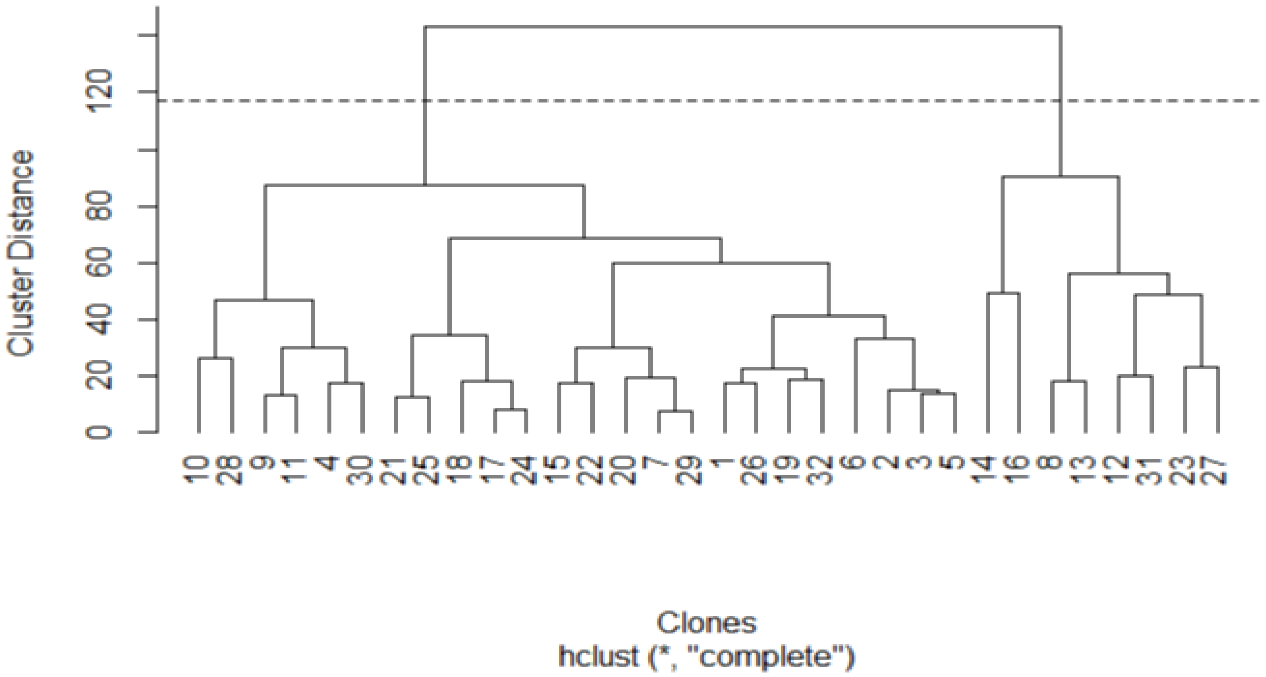


Fig. 1. Cluster analysis (Naturally occurring groups within cultivars of treatment K-40, K-80, K-100, K-120).

Fractionation of soil iron

Potassium application after rice harvest affected the soil's iron content in various chemical forms. Sequential fractionation, as illustrated in Fig. 2, showed that exchangeable iron constituted only 2.02 % of the total iron. Carbonate-bound iron contributed 1.45 to 2.49 % and exhibited an increasing trend with higher potassium application. Oxide-bound iron, which ranged from 16.42 to 28.4 %, also increased with higher potassium doses, following a similar trend to carbonate-bound iron. This form of iron was 1000–2000 times greater than exchangeable iron. Organic-bound iron accounted for 4 to 11 % of the total iron, but did not show a consistent trend with varying potassium doses. Residual iron made up the largest portion of total iron, ranging from 57.6 to 78 %, but showed a declining tendency with increasing potassium doses.

The total iron content, which is the sum of these 5 fractions, ranged from 1963 to 2274 ppm and was not affected by the potassium application doses. Exchangeable iron concentration was found to decrease with increasing potassium doses. Potassium doses significantly negatively correlated with the exchangeable fraction of iron and positively correlated with carbonate-bound, oxide-bound and organic iron as well as DTPA-extractable iron (Table 5). Additionally, there was a significant reduction in DTPA-extractable Fe in post-harvest soil compared to the initial soil Fe levels (Table 1).

Discussion

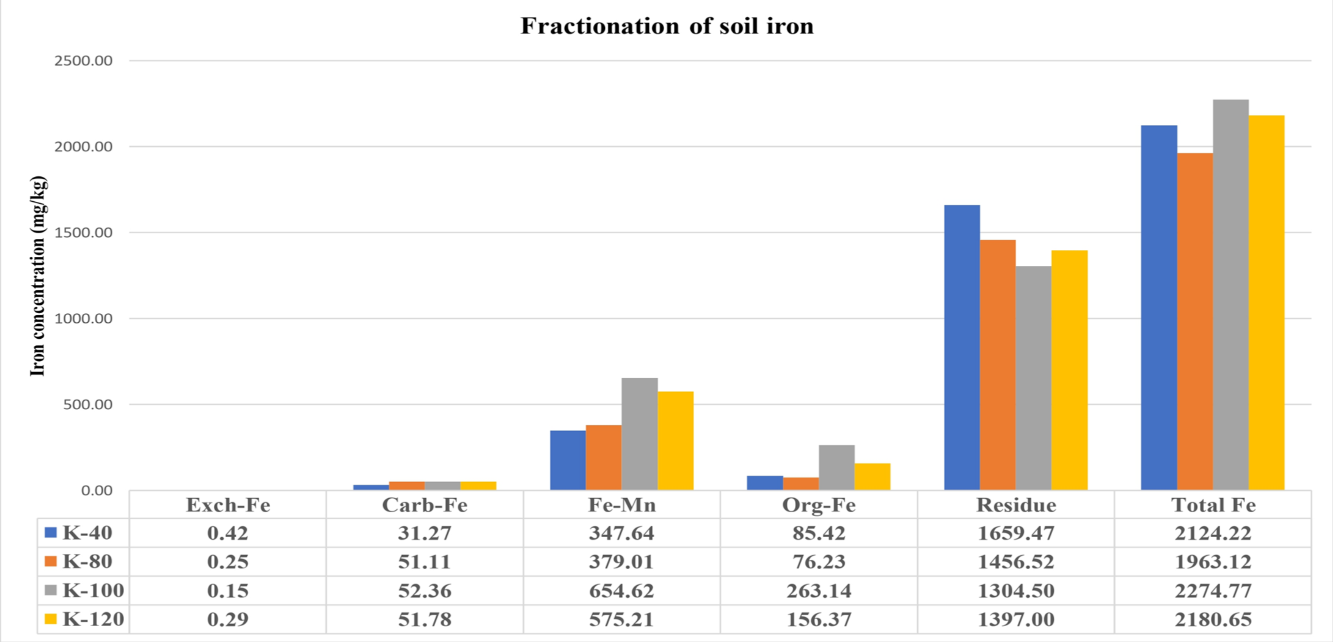
Effect on tiller number, root length and SPAD value at maximum tillering stage

Iron plays a crucial role in several physiological metabolic processes in plants, including the growth of chloroplasts, chlorophyll production, electron transport and redox reactions. At K-40, certain cultivars exhibited signs of iron toxicity, such as a significant increase in tiller number due to altered potassium nutrition, a gradual decrease in root length with higher potassium application and irregular SPAD values. Despite increased potassium treatment, iron uptake progressively declined as potassium application increased. These results suggest that iron acquisition in the roots may facilitate potassium uptake, thereby promoting iron toxicity and reducing the number of tillers. Previous research has also reported a decrease in root length under similar conditions (9). Exposure to excessive iron ions can lead to an imbalance in free radical generation, causing oxidative stress in plants (10).

Table 5. Correlation coefficient among forms of Fe and other parameters

Parameters	K dose	Yield	Fe uptake	DTPA-Fe	Exch-Fe	Carb-Fe	Fe-Mn	Org-Fe	Residual Fe
Yield	0.543								
Fe uptake	-0.774**	-0.626							
DTPA-Fe	0.413	0.894**	-0.771**						
Exch-Fe	-0.895**	-0.826**	0.683*	-0.610					
Carb-Fe	0.902**	0.701*	-0.555	0.419	-0.975**				
Fe-Mn	0.820**	0.803**	-0.963**	0.847**	-0.834**	0.711*			
Org-Fe	0.590	0.886**	-0.882**	0.977**	-0.717*	0.545	0.941**		
Residual Fe	-0.874**	-0.874**	-0.734*	-0.696*	0.994**	-0.943**	-0.880**	-0.791**	
Total Fe	0.365	0.534	-0.871**	0.839**	-0.331	0.134	0.792**	0.859**	-0.424

**** signifies correlated at p value of 0.01, * signifies correlated at p value of 0.05**



	Exch-Fe	Carb-Fe	Fe-Mn	Org-Fe	Residue	Total Fe
🟦 K-40	0.42	31.27	347.64	85.42	1659.47	2124.22
🟧 K-80	0.25	51.11	379.01	76.23	1456.52	1963.12
⬜ K-100	0.15	52.36	654.62	263.14	1304.50	2274.77
🟨 K-120	0.29	51.78	575.21	156.37	1397.00	2180.65

Fig. 2. Differential fractionation of soil iron.

Effect on iron uptake, potassium uptake, grain yield and straw yield

The study revealed that grain yield increased with the potassium fertilization dose, peaking at cultivar K-120. This suggests that potassium deficiency may also result from high iron levels in low-lying areas and poorly drained soil during the wet season (11), a condition that can be mitigated by applying potassium fertilizers. The varied responses of cultivars to potassium management techniques indicate that the issue of iron toxicity can be addressed by combining suitable tolerant varieties with effective soil management practices. Tolerant cultivars that respond positively to potassium nutrition may help mitigate iron toxicity by reducing nutrient uptake by plants. Furthermore, we found a strong correlation between grain production, straw yield, potassium and iron uptake in response to potassium nutrient management.

Grouping of cultivars based on grain yield, iron and potassium content

Cluster analysis revealed 2 naturally occurring groups among the cultivars, categorized based on their priority regarding nutrient uptake and grain yield. Cultivars such as Savitri, Jagabandhu, Hiranmayee, Moti, Pratikshya, Ranidhan, Hasant and Upahar were identified as susceptible to iron-toxic soil conditions, resulting in low yields. On the other hand, Tanmayee, Upahar, Bina dhan-11 and Indravati exhibited extremely high tolerance to iron, with increased yields in response to potassium nutrition. Prachi and Kanchan were classified in the high priority group.

Fractionation of soil iron

After the rice crops were harvested, it was observed that the total iron content in the soil remained unaffected by varying potassium application doses, with concentrations ranging from 1963 to 2274 parts per million (Fig.2). However, the fractions of iron present in the soil were significantly influenced by the application of potassium. The majority of the iron existed in the residual form, suggesting that it was acquired near the rhizosphere soil and not absorbed by the plant; instead, it facilitated potassium absorption by the crop. High concentrations of iron in the root zone affected root length, although there was an increase in grain yield at K-120. This increase may have been caused by a higher % of carbon translocated to the grain and a corresponding decrease in carbon delivered to the roots. Potassium application doses led to a decrease in exchangeable iron, with this form being closely linked to potassium doses. However, compared to other soils, the content of exchangeable iron was found to be extremely low, indicating a positive correlation between potassium fertilization and a reduction in soil iron content. Additionally, potassium had a significant impact on reducing soil iron content, with an increase in potassium content leading to a decrease in plant-available forms of iron, particularly exchangeable iron (12).

Conclusion

These finding confirm that to sustain the crop productivity in iron-toxic low-land rice fields, it is essential to enrich the soil with high-potassium fertilizer and employ suitable rice cultivars. This approach aids in fostering rice growth and maximizing production.

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Authors' contributions

Every author has contributed actively to this work. JS worked in both the lab and in the field. The experiment was conceived and overseen by RKP and RKN. The manuscript was prepared and edited by RKP and JS. RKN and MRS contributed to the result's interpretation and offered criticism.

Compliance with ethical standards

Conflict of interest: The authors declare that there is no conflict of interest.

Ethical issues: None.

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