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Morphological characterisation, genetic variability and grain iron-zinc profiling of indigenous rice (*Oryza sativa* L.) landraces

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Abstract

Traditional rice (*Oryza sativa* L.) landraces possess extensive genetic diversity and are valuable sources of alleles for improving yield, grain quality and nutrition. The present study was conducted at College Farm, Agricultural College, Aswaraopet, during kharif 2024 using 66 indigenous landraces and four standard checks (BPT 5204, Chittimutyalu, DRR Dhan 45 and Zincorice) in an augmented block design. Wide phenotypic diversity was observed for qualitative traits, including culm growth habit, flag leaf orientation, stem anthocyanin pigmentation, awn distribution, leaf colour intensity and kernel colour. Analysis of variance (ANOVA) revealed significant differences for all 14 quantitative traits, confirming substantial genetic variability. Grain yield per plant (GYP) ranged from 12.09 to 34.20 g, plant height from 58.37 to 142.42 cm and number of filled grains per panicle (NFP) from 38 to 142. High genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were observed for GYP, grain iron (Fe) concentration, panicles per plant, NFP and kernel breadth (KB). Most traits exhibited high heritability coupled with high genetic advance as a percentage of mean, indicating predominant additive gene action and effectiveness of direct selection. Grain Fe and zinc (Zn) concentrations ranged from 3.87–15.30 and 10.63–25.48 ppm, respectively. DRR Dhan 45 recorded the highest Fe concentration, while Kumargorla had the highest Zn concentration. Siddhasanna combined higher Zn concentration (21 ppm) with high GYP (30.54 g). These landraces represent promising donor materials for rice biofortification and development of nutritionally enriched, high-yielding cultivars.

Keywords: biofortification; genetic variability; grain iron; grain zinc; indigenous rice landraces; morphological diversity

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1. Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops worldwide and serves as the staple food for more than half of the global population. It plays a crucial role in global food security, nutrition and the livelihoods of millions of people, particularly in developing countries. Owing to its wide adaptability, rice is cultivated across diverse agro-climatic regions under varying production systems, ranging from irrigated and rainfed lowlands to upland ecosystems. Globally, it occupies approximately 165 million hectares worldwide and producing more than 780 million tonnes annually. India is one of the world's leading rice producers and exporters, contributing substantially to global rice production.

During 2024–25, rice was cultivated on approximately 51.3 million hectares in India, with production reaching about 150 million tonnes (United States Department of Agriculture – Foreign Agricultural Service (USDA-FAS), 2025). In Telangana, rice remains a major cereal crop, with production estimated at approximately 17.9 million tonnes during 2024–25, according to the Second Advance Estimates of the Directorate of Economics and Statistics, Government of Telangana (Government of Telangana, 2025). These figures highlight the importance of rice at both national and state levels and emphasise the need to conserve and utilise diverse rice genetic resources for future crop improvement.

The introduction of high-yielding cultivars during the Green Revolution greatly increased rice productivity but also accelerated the replacement of traditional landraces, resulting in a gradual reduction in the genetic diversity available for crop improvement. In contrast, indigenous rice landraces have been maintained by farmers under diverse agro-ecological conditions over generations, preserving a rich reservoir of genetic

diversity. This diversity provides valuable opportunities for effective selection and the development of improved cultivars in rice breeding programmes. Consequently, these resources remain indispensable for broadening the breeding pool and developing rice cultivars with enhanced resilience, productivity and nutritional quality.

Iron (Fe) and zinc (Zn) deficiencies remain among the most widespread forms of micronutrient malnutrition, particularly in regions where rice is the major dietary staple. Polished rice generally contains approximately 2–3 ppm Fe and 10–15 ppm Zn, although these concentrations may vary depending on genotype, growing environment and processing conditions. Due to the relatively low concentrations of these essential minerals, biofortification has become an important breeding strategy for improving human nutrition. Identification of landraces combining high grain micronutrient content with desirable agronomic traits is therefore essential for the development of nutritionally superior rice varieties.

Although India possesses rich collections of indigenous rice germplasm, many landraces have not been comprehensively characterised for agro-morphological traits, grain quality and micronutrient composition. Therefore, the present study was undertaken to evaluate 66 indigenous rice landraces along with 4 checks for qualitative and quantitative morphological traits, estimate grain Fe and Zn concentrations and assess genetic variability, heritability and genetic advance. The information generated will facilitate the identification of promising donor genotypes for rice breeding and biofortification programmes. Such characterisation provides essential information for selecting promising genetic resources that can be effectively incorporated into rice breeding and improvement programmes.

2. Materials and Methods

The experiment was conducted during kharif 2024 at the College Farm, Agricultural College, Aswaraopet, Professor Jayashankar Telangana Agricultural University (PJTAU), Telangana, India. Post-harvest grain quality evaluation and micronutrient estimation were performed during the rabi 2024 at the Central Instrumentation Cell (CIC), College of Agriculture, Rajendranagar, Hyderabad. The experimental set comprised 66 indigenous rice (*O. sativa*) landraces which are farmer's collections from different geographical regions of India together with four check varieties, namely BPT 5204, Chittimutyalu, DRR Dhan 45 and Zincorice. The genotypes were evaluated using an augmented block design in 2 blocks following the procedure described by previous researchers (1). Seedlings were raised in a nursery and transplanted 30 days after sowing. Each genotype was planted in 3 rows of 1.0 m length with a spacing of 20 cm between rows and 15 cm between plants. The check varieties were included repeatedly in each block, whereas the landraces were accommodated as unreplicated test entries. The crop was raised following the recommended package of practices for transplanted rice under the agro-climatic conditions of Telangana. A recommended fertiliser dose of 120 : 60 : 40 kg ha^{-1} N : P_2O_5 : K_2O was applied, with nitrogen supplied in split doses at appropriate crop growth stages. Irrigation was provided at regular intervals according to crop requirement and prevailing weather conditions. Weed, insect-pest and disease management practices were followed as recommended for rice production, with plant protection measures adopted whenever required. All genotypes were subjected to uniform crop management practices throughout the experiment. Morphological characterisation was performed using the standard rice descriptor guidelines (2). Qualitative observations included coleoptile colour, anthocyanin pigmentation, culm attitude, flag leaf attitude, awn characteristics, leaf colour intensity, grain shape and kernel colour. Quantitative observations were recorded from five randomly selected plants in each genotype for days to 50 % flowering (DFF), days to maturity (DM), plant height (PH), panicle length (PL), number of panicles per plant (NPP), number of filled grains per panicle (NFP), 1000-grain weight (TGW) and grain yield per plant (GYP). Grain length (GL), grain width (GW), kernel length (KL) and kernel breadth (KB) were measured using a digital Vernier caliper. Representative grain samples from each genotype were used for the estimation of iron (Fe) and zinc (Zn) concentrations. The grain samples were cleaned to remove adhering dust and foreign material, oven-dried to constant weight and finely ground using a stainless-steel grinder. Approximately 0.5 g of powdered grain sample was accurately weighed into a digestion tube and subjected to wet-acid digestion using concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$). The samples were heated gradually until a clear digest was obtained. After cooling, the digest was filtered and the volume was made up to a known volume with deionised water. Iron and Zn concentrations in the digested samples were determined using a Flame Atomic Absorption Spectrophotometer (PerkinElmer PE4000) at the Central Instrumentation Cell, Rajendranagar. Reagent blanks were processed along with the samples to account for background contamination and standard solutions of Fe and Zn were used for instrument calibration. Quality control was maintained through analysis of blanks and repeated measurements of selected samples. The concentrations of Fe and Zn were expressed as parts per million (ppm). Representative grain samples from each genotype were analysed for Fe and Zn concentrations using a Flame Atomic Absorption Spectrophotometer (PerkinElmer PE4000) at the Central Instrumentation Cell, Rajendranagar. The concentrations of both micronutrients were expressed as parts per million (ppm).

Statistical analysis and genetic variability studies

Analysis of variance (ANOVA) was employed to examine the presence of significant differences among the rice genotypes for the quantitative traits evaluated. Statistical analyses were performed using R statistical software (version 4.3.2). The significance of differences among treatments/genotypes was tested at $p \leq 0.05$. The degree of genetic variability was quantified by estimating genotypic coefficient of variation (GCV) and phenotypic

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coefficient of variation (PCV). To determine the extent to which observed variation was genetically controlled, broad-sense heritability was estimated and genetic advance expressed as a percentage of the mean was calculated to predict the potential response to selection. Together, these genetic parameters provided insights into the inheritance pattern of the traits and facilitated the identification of characters with high breeding value for rice improvement and biofortification programmes

Analysis of variance

The analysis of variance was performed following augmented block design as suggested earlier (1).

Genotypic and phenotypic coefficients of variance

The genotypic and phenotypic coefficients of variation were calculated according to the formula given by previous researchers (3).

Phenotypic co-efficient of variation

$$PCV = \frac{\sigma_p}{\bar{X}} \times 100$$

Where,

σ_p = Phenotypic standard deviation

$\bar{X}$ = General mean

Genotypic co-efficient of variation

$$GCV = \frac{\sigma_g}{\bar{X}} \times 100$$

Where,

σ_g = Genotypic standard deviation

$\bar{X}$ = General mean

< 10 %-low, 10–20 %-moderate , > 20 %-high

Heritability

The broadest sense heritability (h^2) was estimated using the following formula (4)

$$h^2 = \frac{V_g}{V_p} \times 100$$

h^2 = Broad sense heritability expressed in per cent

V_g = Genotypic variance

V_p = Phenotypic variance

Genetic advance (Expected)

The expected genetic advance was calculated by using the following formula as suggested previously (5).

$GA = k \times h^2 \times \sqrt{Vp}$

Where,

k = Selection differential which is equal to 2.06 at 5 % selection intensity, respectively.

h^2 = Broad sense heritability

$\sqrt{Vp}$= Phenotypic standard deviation

Genetic advance as per cent for mean was calculated as below

GAM (%) =

(Genetic advance (GA))/(Trait grand mean ($\bar{X}$) ×100

3. Results

Morphological characterisation

Morphological evaluation of the rice germplasm revealed considerable variation for several qualitative traits. Coleoptile colour was assessed visually at 15 days after sowing and all 70 genotypes exhibited colourless coleoptiles. Leaf sheath anthocyanin pigmentation was absent in all the evaluated genotypes. Ligule characteristics showed limited variation, with ligules present in all 70 genotypes; 64 genotypes exhibited acute ligules and six exhibited split ligules. Ligule colour also varied among the genotypes, with white ligules recorded in 58 genotypes and purple ligules in 12 genotypes.

Variation was also observed for culm growth habit during the booting stage. Among the evaluated genotypes, 58 exhibited an erect culm, whereas six each displayed semi-erect and spreading growth habits. Flag leaf attitude, recorded approximately 60 days after sowing (DAS), differed among the genotypes, with 10 showing erect leaves, 48 semi-erect leaves and 12 horizontal leaves. Leaf colour intensity, assessed at around 40 DAS, ranged from light green to dark green. Thirty-seven genotypes possessed light green foliage, 28 had medium green leaves and five exhibited dark green leaves.

Stem anthocyanin pigmentation was another variable morphological trait. Purple pigmentation was observed in 20 genotypes, whereas the remaining 50 genotypes lacked anthocyanin pigmentation. Evaluation at the ripening stage revealed that awns were present in 14 genotypes and absent in 56 genotypes, accounting for all 70 genotypes evaluated. Kernel colour exhibited considerable diversity, with 40 genotypes producing white kernels, 15 brown kernels, 13 red kernels and 2 black kernels (Table 1).

Analysis of variance

Analysis of variance revealed significant differences among the genotypes for all 14 quantitative characters, viz., DFF, DM, PH (cm), PL(cm), NPP, NFP, GYP (g), GL (mm), GW (mm), TGW (g), KL (mm), KB (mm), grain Fe concentration (ppm) and grain Zn concentration (ppm) (Table 2). Significant block effects in the unadjusted analysis, together with significant treatment effects in both adjusted and unadjusted analyses, indicated the presence of substantial variability among the evaluated genotypes. Significant differences were also observed among checks, test genotypes (landraces) and for the contrast between checks and test genotypes, indicating variation among the rice landraces and checks for the traits evaluated.

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Table 1. Morphological characterisation of 66 rice landraces and four check varieties based on qualitative traits

Sl. No.	Accession No.	Coleoptile colour	Intensity of green colour in leaves	Leaf anthocyanin colouration	Leaf ligule	Culm type	Flag leaf attitude	Panicle awn	Stem anthocyanin colouration	Kernel colour
1	Bhajana	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	Brown
2	Kalalangad	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	Brown
3	Kudrath	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	White
4	Saphari	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
5	Tarang	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
6	Kandasagar	Colourless	Medium	Absent	Present	Semierect	Semierect	Absent	Absent	White
7	Panchatantra	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	White
8	Budamalu	Colourless	Medium	Absent	Present	Erect	Horizontal	Absent	Present	Brown
9	Ghalima	Colourless	Light	Absent	Present	Erect	Semierect	Present	Present	White
10	Bammagutni	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	White
11	Sugandhi	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	White
12	Haladhichudi	Colourless	Light	Absent	Present	Erect	Erect	Absent	Present	White
13	Dhimidi	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
14	Barhavahi	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	Brown
15	Sonamali	Colourless	Light	Absent	Present	Erect	Erect	Present	Present	White
16	Gadakodimamahi	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Brown
17	Rahikanda	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
18	Agmakunda	Colourless	Medium	Absent	Present	Spreading	Semierect	Absent	Absent	Brown
19	Indrani	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
20	Methimahal	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
21	Sannajajulu	Colourless	Light	Absent	Present	Erect	Erect	Absent	Absent	White
22	Redjasmine	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	White
23	Bahurupi	Colourless	Medium	Absent	Present	Spreading	Semierect	Present	Present	White
24	Daddiga	Colourless	Light	Absent	Present	Spreading	Semierect	Present	Present	White
25	Kiatampetasannalu	Colourless	Light	Absent	Present	Erect	Erect	Present	Present	White
26	Zeerashankar	Colourless	Light	Absent	Present	Erect	Horizontal	Present	Present	Red
27	Kundadam	Colourless	Medium	Absent	Present	Erect	Erect	Absent	Absent	Brown
28	Chandrogadah	Colourless	Medium	Absent	Present	Erect	Semierect	Present	Present	White
29	Bhalududium	Colourless	Light	Absent	Present	Erect	Semierect	Present	Present	Brown
30	Kantamuguni	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	Red
31	Tikkimisri	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	Brown
32	Kalajeel	Colourless	Dark	Absent	Present	Semierect	Semierect	Absent	Absent	White
33	Assamchudi	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Brown
34	Kalimuch	Colourless	Dark	Absent	Present	Semierect	Semierect	Absent	Absent	White
35	Ramkul	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	White
36	Ambemohar	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	Red
37	Gedikahiye	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	White
38	Illapusamba	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Red
39	Javapoola	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Red

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40	302	Colourless	Medium	Absent	Present	Semierect	Semierect	Absent	Absent	White
41	Hembarbag	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	Red
42	Kakirekkalu	Colourless	Medium	Absent	Present	Erect	Horizontal	Absent	Present	Red
43	Karamguruvay	Colourless	Light	Absent	Present	Erect	Semierect	Present	Present	Red
44	Birodlu	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	White
45	Mudimurangi	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	Brown
46	Ramjeera	Colourless	Light	Absent	Present	Erect	Erect	Absent	Present	Red
47	Hallabatta	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
48	Vedurusanna	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	White
49	Pohaki	Colourless	Light	Absent	Present	Erect	Erect	Present	Present	Brown
50	Nagara	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Brown
51	Lathisali	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Brown
52	Esakarvad	Colourless	Medium	Absent	Present	Spreading	Semierect	Absent	Absent	White
53	Radhajigil	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Brown
54	Kumargorla	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
55	Thonda	Colourless	Light	Absent	Present	Erect	Erect	Absent	Absent	White
56	Jajudhan	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	Brown
57	Ambemohar-2	Colourless	Medium	Absent	Present	Spreading	Semierect	Present	Present	White
58	Raktasali	Colourless	Medium	Absent	Present	Spreading	Semierect	Present	Present	White
59	Siddhasanna	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Red
60	Aasudhi	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	Red
61	Kouthrimaharaj	Colourless	Medium	Absent	Present	Semierect	Semierect	Absent	Absent	White
62	Kujipabali	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	Red
63	Chintabarisannalu	Colourless	Medium	Absent	Present	Erect	Horizontal	Absent	Present	Red
64	Manipurblack	Colourless	Light	Absent	Present	Erect	Semierect	Present	Present	Red
65	Redrice	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	White
66	Kalabatta	Colourless	Light	Absent	Present	Erect	Horizontal	Absent	Absent	Brown
67	Chittimutyalu	Colourless	Light	Absent	Present	Erect	Erect	Absent	Present	Red
68	DRRDhan45	Colourless	Medium	Absent	Present	Erect	Semierect	Absent	Absent	White
69	BPT5204	Colourless	Light	Absent	Present	Erect	Semierect	Absent	Absent	White
70	Zincorice	Colourless	Light	Absent	Present	Erect	Erect	Present	Present	Brown

Table 2. Analysis of variance for 14 quantitative traits in 66 rice landraces and four check varieties evaluated in an augmented block design

Source of variation	d.f	DFF	DM	PH	PL	NPP	NFP	GL	GW	TGW	KL	KB	FC	ZC	GYP
Block (ignoring Treatments)	2.00	27.04**	24.05**	366.69**	6.5**	61.65**	681.32**	15.6**	0.31**	3.24*	2.24**	0.34**	9.33**	23.03**	45.27**
Treatment (eliminating Blocks)	69.00	46.23**	38.99**	302.72**	11.26**	7.28**	655.19**	1.99**	0.41**	15.2**	1.05**	0.24**	10.94**	11.85**	31.58**
Checks + varieties vs. varieties	66.00	46.88**	36.04**	314.89**	9.29**	7.59**	50.04**	0.77**	0.24**	12.86**	0.91**	0.24**	11.42**	12.33**	32.98**
Block (eliminating Check+var.) (adj)	2.00	0.25ns	0.75ns	0.41ns	0.16ns	0.25ns	0.33ns	0.03ns	0.03ns	0.1ns	0.01ns	0.01ns	0.15ns	0.08ns	0.11ns

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Entries (ignoring Blocks)(adj)	69.00	47.01**	39.66**	313.34**	11.45**	9.05**	674.91**	2.44**	0.42**	15.29**	1.11**	0.25**	21.73**	19.56**	32.88**
Checks	3.00	32.08**	103.86**	34.87**	54.56**	2.31**	0.89**	4.65**	0.26**	66.73**	4.06**	0.25**	0.52**	1.3**	0.66**
Varieties	65.00	29.13**	37.06**	225.49**	2.29**	7.8**	643.71**	2.29**	0.43**	13.09**	0.25**	0.34**	6.7**	10.39**	33.33**
Checks vs.Varieties	1.00	1254.13**	16.25*	447.16**	2.02**	110.27**	4723.43**	2.46**	0.22**	3.74**	1.16**	0.11*	336.15**	184.82**	100.69**
Error	6.00	1.25	1.86	0.02	0.05	0.56	1.42	0.0017	0.00046	0.08	0.0032	0.0031	0.09	0.02	0.09

d.f: degrees of freedom; *Indicates significance at 5 % probability level,** indicates significance at 1 % probability level.

DFF: days to 50 % flowering, DM: days to maturity, PH: plant height (cm), PL: panicle length (cm), NPP: number of panicles per plant, NFP: number of filled grains per panicle, GYP: grain yield per plant (g), GL: grain length (mm), GW: grain width (mm), TGW: 1000-grain weight (g), KL: kernel length (mm), KB: kernel breadth (mm), FC: Fe (iron) content (ppm), ZC: Zn (zinc) content (ppm).

Genetic variability parameters: Genotypic coefficient of variation, phenotypic coefficient of variation, heritability and genetic advance

Estimates of GCV, PCV, broad-sense heritability and genetic advance as a percentage of the mean were computed for all 70 genotypes and the results are presented in Table 3. Considerable variation was observed among the quantitative traits, with differences in the magnitude of GCV, PCV, heritability and genetic advance.

Days to 50 % flowering exhibited low GCV (6.10 %) and PCV (6.12 %), with very high heritability (99.54 %) and moderate genetic advance as a percentage of the mean (12.56 %). Days to maturity also recorded low GCV (4.67 %) and PCV (4.75 %), along with high heritability (96.78 %) and genetic advance as a percentage of the mean (9.48 %). Plant height exhibited moderate GCV (17.67 %) and PCV (17.67 %), with very high heritability (99.99 %) and high genetic advance as a percentage of the mean (36.45 %). Panicle length recorded moderate GCV (21.28 %) and PCV (21.30 %), high heritability (99.79 %) and high genetic advance as a percentage of the mean (43.85 %).

The NPP exhibited high GCV (32.39 %) and PCV (33.61 %), with high heritability (92.88 %) and high genetic advance as a percentage of the mean (64.60 %). Similarly, the NFP recorded high GCV (30.81 %) and PCV (30.85 %), very high heritability (99.78 %) and high genetic advance as a percentage of the mean (63.50 %).

Grain length exhibited moderate GCV (10.07 %) and PCV (10.33 %), with high heritability (95.07 %) and genetic advance as a percentage of the mean (20.26 %). Grain width recorded moderate GCV (16.88 %) and PCV (18.63 %), together with high heritability (82.13 %) and high genetic advance as a percentage of the mean (31.56 %). The TGW exhibited moderate GCV (16.96 %) and PCV (17.01 %), high heritability (99.42 %) and high genetic advance as a percentage of the mean (34.88 %). Kernel length recorded moderate GCV (14.81 %) and PCV (14.83 %), high heritability (99.67 %) and high genetic advance as a percentage of the mean (30.49 %). Kernel breadth exhibited high GCV (24.76 %) and PCV (24.91 %), high heritability (98.78 %) and high genetic advance as a percentage of the mean (50.77 %).

Grain iron concentration exhibited high PCV (27.99 %) and GCV (27.80 %), high heritability (98.62 %) and high genetic advance as a percentage of the mean (56.95 %). Grain zinc concentration recorded moderate GCV (18.98 %) and PCV (19.00 %), very high heritability (99.80 %) and high genetic advance as a percentage of the mean (39.12 %). Grain yield per plant exhibited high GCV (26.33 %) and PCV (26.36 %), very high heritability (99.72 %) and high genetic advance as a percentage of the mean (54.23 %) (Fig. 1 and 2, Table 3).

Table 3. Genetic variability parameters for 14 quantitative traits in rice landraces (*Oryza sativa*)

Sl. No.	Characters	General mean	Range		PCV (%)	GCV (%)	h2	GA as percent of mean (at 5 %)
			Minimum	Maximum				
1.	Days to 50 % flowering	89.00	74.00	104.00	6.12	6.10	99.54	12.56
2.	Days to maturity	128.00	108.00	137.00	4.75	4.67	96.78	9.48
3.	Plant height (cm)	84.97	58.37	142.42	17.67	17.67	99.99	36.45
4.	Panicle length (cm)	21.05	13.62	31.39	21.30	21.28	99.79	43.85
5.	Number of panicles per plant	8.00	2.00	14.00	33.61	32.39	92.88	64.60
6.	Number of filled grains per panicle	82.00	38.00	142.00	30.85	30.81	99.78	63.50
7.	Grain length (mm)	8.34	6.19	9.98	10.33	10.07	95.07	20.26
8.	Grain width (mm)	2.80	2.05	3.98	18.63	16.88	82.13	31.56
9.	1000 grain weight (g)	21.28	2.11	29.25	17.01	16.96	99.42	34.88

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10.	Kernel length (mm)	6.66	4.19	8.95	14.83	14.81	99.67	30.49
11.	Kernel breadth (mm)	2.02	0.98	2.98	24.91	24.76	98.78	50.77
12.	Fe content (ppm)	9.25	3.87	15.30	27.99	27.8	98.62	56.95
13.	Zncontent (ppm)	16.97	10.63	25.48	19.00	18.98	99.80	39.12
14.	Grain yield per plant (g)	21.90	12.09	34.20	26.36	26.33	99.72	54.23

PCV: phenotypic coefficient of variation; GCV: genotypic coefficient of variation; h^2: broad-sense heritability; GA: genetic advance; Fe: iron; Zn: zinc.

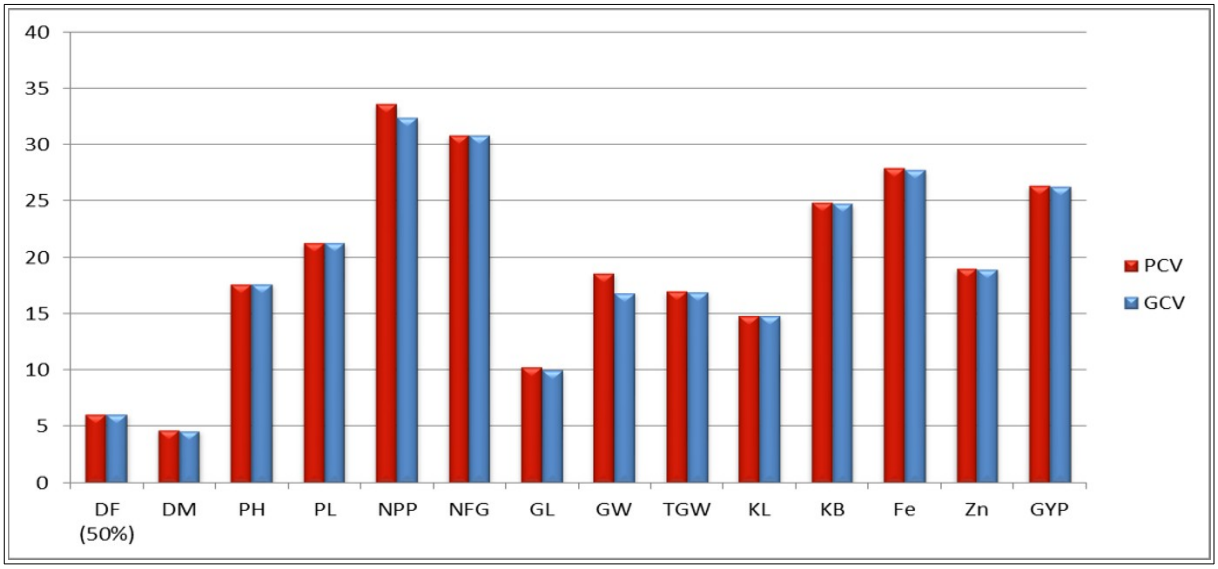


Fig. 1. Histogram of phenotypic co-efficient of variation (PCV) and genotypic co-efficient of variation (GCV) for grain yield and its component characters in 70 genotypes.

DF (50 %): days to 50 % flowering; DM: days to maturity; PH: plant height (cm); PL: panicle length (cm); NPP: number of panicles per plant; NFG: number of filled grains per panicle; GL: grain length (mm); GW: grain width (mm); TGW: 1000-grain weight (g); KL: kernel length (mm); KB: kernel breadth (mm); Fe: iron content (ppm); Zn: zinc content (ppm); GYP: grain yield per plant (g).

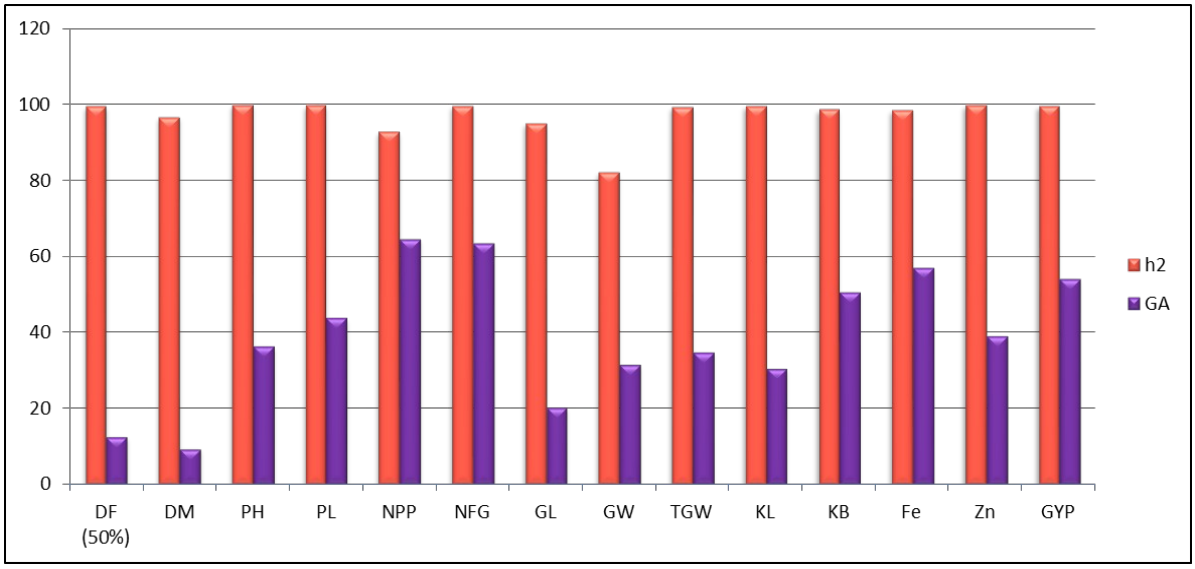


Fig. 2. Histogram of heritability and genetic advance for grain yield and its component characters in 70 genotypes.

DF (50 %): days to 50 % flowering; DM: days to maturity; PH: plant height (cm); PL: panicle length (cm); NPP: number of panicles per plant; NFG: number of filled grains per panicle; GL: grain length (mm); GW: grain width (mm); TGW: 1000 grain weight (g); KL: kernel length (mm); KB: kernel breadth (mm); Fe: iron content (ppm); Zn: zinc content (ppm); GYP: grain yield per plant (g).

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Nutritional parameters

The mean grain Fe concentration across the 70 genotypes was 9.25 ppm, with a range of 3.87–15.30 ppm. The lowest grain Fe concentration was recorded in Jajudhan (3.87 ppm), whereas the highest was recorded in the check DRR Dhan 45 (15.30 ppm).

The mean grain Zn concentration was 16.97 ppm, with a range of 10.63–25.48 ppm. Panchatantra recorded the lowest grain zinc concentration (10.63 ppm), whereas Kumargorla recorded the highest (25.48 ppm).

Based on the predefined concentration categories, the genotypes were classified into low, moderate and high groups for grain Fe and Zn concentration (Fig. 3 and 4). For Fe, concentrations below 9.0 ppm were classified as low, 9.1–15.0 ppm as moderate and above 15.1 ppm as high. Accordingly, 41 genotypes were classified as low, 28 as moderate and one as high. For Zn, concentrations below 16.0 ppm were classified as low, 16.1–19.0 ppm as moderate and above 19.1 ppm as high, comprising 29, 27 and 14 genotypes, respectively (Table 4).

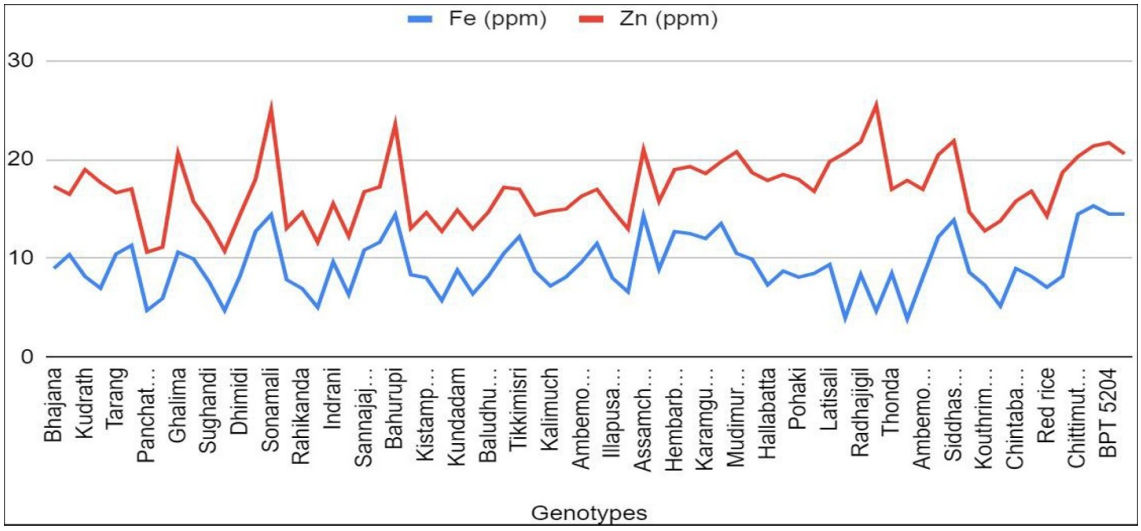


Fig. 3. Variation in iron (Fe) and zinc (Zn) micronutrient content in 70 rice genotypes.

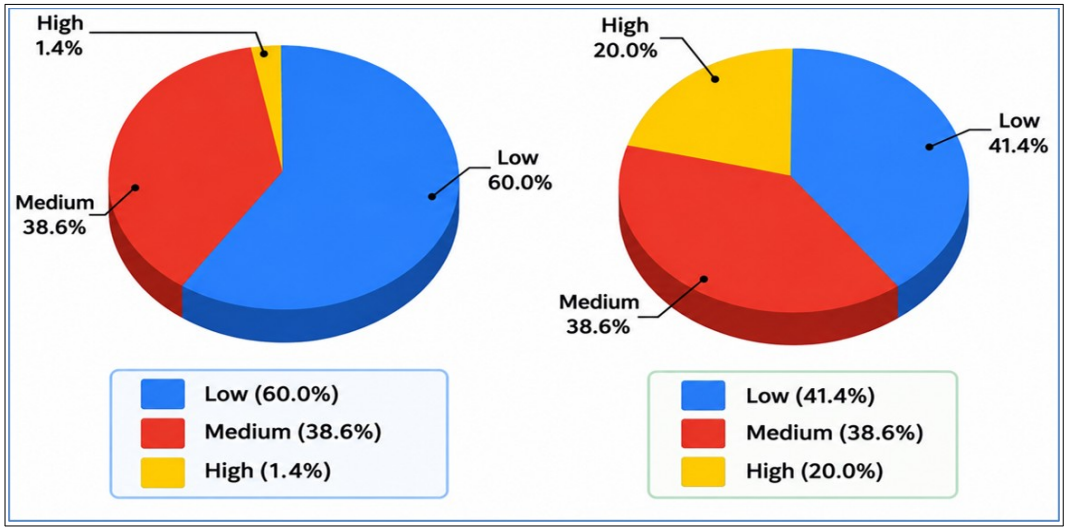


Fig. 4. Classification of genotypes based on iron (Fe) and zinc (Zn) content.

Table 4. Classification of genotypes based on iron and zinc content

Category	Iron (Fe)	Zinc (Zn)
Low	Bhajana, Kudrath,Saphari, Panchatantra, Budamalu, Sughandi, Dhimidi, Haladichudi, Esakarvad, Kumargorla, Jajudhan, Gadakodimamahi, Rahikanda, Agmakunda, Methimahal, Daddiga, Kistampetasannalu, Zeerashankar, Ambemohar-2, Kundadam, Chandrogadah, Balududium, Kalajeel, Kalimuch,	Panchatantra, Budamalu, Sughandi, Haladichudi, Dhimidi, Gadakodimamahi, Rahikanda, Agmakunda, Indrani, Methimahal, Daddiga, Kistampetasannalu,Bammagutni, Zeerashankar, Kundadam, Chandrogadah, Balududium, Kalajeel, Kalimuch, Ramkul, Illapusamba, 302, Javapoola, Ambemohar-2, Aasudhi, Kouthrimaharaj, Chintabarisannalu,

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	Ramkul, Illapusamba, Javapoola, 302, Hallabatta, Vedurusanna, Pohaki, Nagara, Radhajigil,Thonda, Ambemohar, Aasudhi, Kouthrimaharaj, Kujipabali, ChintabariSannalu, Manipur Black, Red Rice and Kalabatta.	Kujipabali and Red Rice.
Moderate	Kalalangad, Bammagutni, Indrani, Ambemohar, Ramjeera, Latisali, Chittimutyalu, BPT 5204, Zincorice, Raktasali, Siddasanna, Gedikahiye, Assamchudi, Hemberbag, Kakirekkalu, Birodlu, Mudimurangi, Tikkimisri, Kantamuguni, Sannajajulu, Red Jasmine, Bahurupi, Barhavahi, Sonamali, Ghalima, Tarang and Kandasagar.	Bhajana, Kalalangad, Kudrath, Saphari, Tarang, Kandasagar, Barhavahi, Sannajajulu, Red Jasmine, Kantamuguni, Tikkimisri, Gedikahiye, Hembarbag, Kakirekkalu, Karamguruvay, Birodlu, Ramjeera, Hallabatta, Vedurusanna, Pohaki, Nagara, Latisali, Jajudhan, Thonda, Ambemohar, Manipur Black and Kalabatta
High	DRR Dhan 45	Ghalima, Kumargorla, Bahurupi, Sonamali, Assamchudi, Mudimurangi, Esakarvad, Radhajigil, Raktasali, Siddasanna, Chittimutyalu, DRR Dhan 45, BPT 5204 and Zincorice.

4. Discussion

The evaluated indigenous rice landraces exhibited considerable diversity for both qualitative and quantitative morphological traits, indicating substantial variation within the germplasm evaluated. Variation was particularly evident for ligule characteristics, culm attitude, flag leaf orientation, stem anthocyanin pigmentation, awn distribution and kernel colour. Similar morphological variation has been reported in rice germplasm and landraces, where differences in qualitative descriptors have been useful for varietal characterisation, identification and conservation of genetic resources (6-8). In the present study, the variation in kernel colour, leaf orientation and pigmentation characteristics further confirms the distinctiveness of the evaluated landraces. Comparable diversity among rice landraces has also been documented in agro-morphological characterisation studies from Bangladesh and other rice-growing regions (9).

The analysis of variance revealed significant differences among genotypes for all 14 quantitative traits, demonstrating substantial phenotypic variation in the evaluated material. Similar genetic variability for yield and yield-associated traits has been reported in rice genotypes (10, 11). The present findings are also consistent with previous studies, which reported considerable variation for yield and quality-related traits in rice germplasm (12). Likewise, previous reports observed substantial variability for several agronomic traits, supporting the usefulness of diverse germplasm for selection and breeding (13). The significant variation observed in the present study therefore provides a broad basis for identifying genotypes with desirable combinations of yield, grain quality and nutritional traits.

The estimates of GCV and PCV further demonstrated differences in the magnitude of genetic and phenotypic variation among the traits. For most characters, the relatively small differences between GCV and PCV suggest that environmental effects had a comparatively limited influence on their phenotypic expression under the conditions of the present experiment. Similar trends have been reported for agronomic traits in rice, where close GCV and PCV estimates were associated with substantial genetic variability (11, 14). Appreciable genetic variability for yield and quality traits was also reported by earlier researchers, emphasising the usefulness of such variation for selection (12). In the present material, the comparatively high variability observed for traits such as grain yield, grain dimensions and micronutrient concentration indicates that these characters could provide useful variation for breeding and selection.

High heritability coupled with high genetic advance was observed for several traits, including PH, PL, NPP, NFP, TGW, kernel dimensions, GYP and grain Fe and Zn concentrations. Similar combinations of heritability and genetic advance have been reported for yield and yield-associated traits in rice (11, 14). Substantial genetic variability for grain quality traits among indigenous rice landraces has also been reported previously (15). The high heritability and genetic advance observed in the present study indicate a substantial genetic contribution to the observed phenotypic variation and suggest good potential response to selection. However, broad-sense heritability encompasses different components of genetic variance; therefore, the present estimates alone should not be interpreted as direct evidence of additive gene action. The observed inheritance parameters nevertheless indicate that these traits may respond favourably to selection within the evaluated germplasm.

Grain yield per plant showed high GCV and PCV, together with high heritability and genetic advance, indicating considerable variation among the evaluated landraces. Comparable levels of variability and favourable heritability estimates for yield traits have been reported in rice populations by previous researchers (10, 13, 16). The close correspondence between GCV and PCV in the present study further suggests relatively limited environmental influence on the expression of grain yield under the experimental conditions. Such variability provides opportunities for identifying landraces combining high yield with desirable grain and nutritional characteristics.

The grain quality traits also exhibited substantial variability. Kernel length and KB showed moderate to high levels of genetic variation, while their high heritability and genetic advance indicate considerable scope for

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selection. Similar variability for grain quality traits in indigenous rice landraces has been reported previously (15). The present results therefore support the value of indigenous landraces not only as sources of agronomic variation but also as potential sources of desirable grain-quality characteristics.

Considerable variation was also observed for grain Fe and Zn concentrations. The mean Fe concentration was 9.25 ppm, ranging from 3.87 ppm in Jajudhan to 15.30 ppm in DRR Dhan 45, while Zn concentration ranged from 10.63 ppm in Panchatantra to 25.48 ppm in Kumargorla, with a mean of 16.97 ppm. The wide range observed in the present study is consistent with previous reports demonstrating substantial genetic variation for grain micronutrient concentration in traditional rice germplasm. (17) identified considerable diversity for grain Fe and Zn, together with β-carotene, among traditional rice genotypes, while another study documented variation in Fe and Zn concentrations among traditional rice genotypes (18). These studies support the present observation that indigenous germplasm can provide useful variation for grain micronutrient improvement.

The highest Fe concentration recorded in DRR Dhan 45 and the highest Zn concentration recorded in Kumargorla indicate that these genotypes possess relatively desirable micronutrient levels within the material evaluated. However, differences in micronutrient concentrations among studies may arise from differences in genotype composition, growing environment, soil characteristics, crop season and analytical procedures. Therefore, the present values should be interpreted primarily as indicators of relative diversity within the evaluated germplasm rather than as fixed genotype-specific nutrient concentrations. The high heritability and genetic advance observed for grain Fe and Zn further indicate that genetic variation contributes substantially to the observed differences and that these traits may be useful targets for selection. Similar genetic parameters for grain iron have been reported by earlier researchers (19).

5. Conclusion

The indigenous rice landraces exhibited substantial genetic diversity for agronomic, grain quality and micronutrient traits, providing valuable resources for rice improvement. High heritability coupled with high genetic advance for several traits indicated good prospects for selection. Wide variation in grain iron (Fe) and zinc (Zn) concentrations enabled the identification of genotypes with enhanced micronutrient content for potential use in biofortification programmes. Landraces with desirable agronomic traits and enhanced Fe and/or Zn concentrations may serve as potential donor materials for developing high-yielding, nutritionally improved rice cultivars.

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Authors' contributions

MRS, GKMK, BK, MS, RPM and MA contributed to synopsis preparation, research supervision, monitoring and data analysis. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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