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RESEARCH ARTICLE

Evaluation of Colored Grain Sorghum [*Sorghum bicolor* (L.) Moench] Genotypes for Yield and Quality Traits

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Abstract

Sorghum is a staple cereal food crop of the semi-arid tropics and has nutritional importance. Iron, zinc and protein contents in grains are important for human health. Keeping this in view, 100 colored grain sorghum genotypes along with four check varieties were assessed for grain yield, Iron (Fe), and Zinc (Zn) content and total protein content and also studied the association among these parameters. The protein, Fe, and Zn content of genotypes varied from 4.0 to 20.10 mg/100 mg, 19.51 to 59.94 mg/kg, and 8.36 to 51.11 mg/kg, respectively. All three biochemical parameters were positively correlated with grain yield. Among biochemical parameters, grain Fe content was positively correlated with grain Zn content (r = 0.9216). Based on the results, it can be concluded that there was more variation in the biochemical parameters studied in the genotypes. The identified high-yielding genotypes with more grain Fe, Zn, and protein can be used in biofortified varietal development, and the genotypes with high nutritional content with low yield can be used in a hybridization program to transfer high Fe, Zn, and protein content to the high-yielding genotypes of sorghum.

Keywords: Grain yield, Iron, Protein and correlation, Sorghum and zinc.

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Introduction

Sorghum (*Sorghum bicolor* (L.) Moench], also known as jowar, is a coarse cereal crop that has earned the titles like "King of millets," "great millet," and "the King of coarse cereals." It is the fifth most important cereal crop worldwide in terms of production and utilization. It is often referred to as a failsafe crop and the camel of crops due to its remarkable drought and heat tolerance properties, as well as its high photosynthetic efficiency. Consequently, it is an important staple food crop in arid and semi-arid regions globally, originating from Africa. In India, it is grown in an area of approximately 4.24 million hectares, with a production of 4.78 million metric tonnes and a productivity of 1130 kg/ha during the year 2021 (Anon., 2022). The crop is a diploid (2n = 20) and C_4 grass species that belongs to the family "Graminae" and the tribe "Andropogeneae".

Colored sorghum grains exhibit a wide range of colors, from white to pink, orange, red, and brown, with the pericarp pigmentation and thickness, as well as the presence of a testa influencing the grain color. The nutritional composition of sorghum grain varies with the pericarp color. Phenolic compounds, particularly tannin, contribute to the pigmentation of the pericarp and testa (Sedghi *et al*., 2012). Dykes *et al*. (2009) reported that the composition of flavonoids in red sorghum is related to its R_Y_ genes for red pericarp. Black pericarp grain has high levels of phenolic compounds, especially 3-deoxyanthocyanidins (3-DOAs), which act as an antioxidant (Pfeiffer and Rooney, 2016). Genetic variability studies were carried out in colored grain sorghum for grain yield and biochemical parameters (Kiran, 2021; Akshaykumar, 2022; Kiran *et al*., 2022 and 2023; Akshaykumar *et al*., 2023 and 2024 and Kallanagouda, 2023). Protein, Fe, and Zn are required for human health. Consumption of sorghum with enhanced levels of these nutrients helps in improving human health. Genetic variation in the crop is critical for improving the trait of interest. Fe and Zn being quantitatively inherited (Ashok Kumar *et al*., 2018), deciphering the genetic architecture of these characters is very essential for the development of micronutrient-efficient genotypes and more protein containing genotypes. Earlier studies showed that there exists considerable genetic variability for grain protein, Fe, and Zn concentration in sorghum (Suvarna, 2019 and Kiran, 2021 for protein and; Akshay Kumar, 2022 and Kallanagouda, 2023 for protein, Fe, and Zn content). The largest variability for grain Fe and Zn in sorghum was found in the germplasm and it is feasible to exploit this variation by understanding the genetic control of grain Fe and Zn (Ashok Kumar *et al.,* 2013). Further, it was indicated that it is possible to breed sorghum with enhanced levels of micronutrients (Fe and Zn) in desirable maturity backgrounds (Nguni *et al*., 2012; Ashok Kumar *et al.,* 2013).

Intensive plant breeding programs have increased yields of sorghum grain, but little attention has been paid to the nutritional quality of the grain. Therefore, the objective of this study was to study the compositional variation in mineral elements (Fe and Zn) and protein content in grains of different colored sorghum genotypes and to determine the association between them.

Material and Methods

The material used for the present study included 100 colored grain sorghum genotypes with different pericarp colors obtained from R.S. Paroda gene bank, ICRISAT, Patancheru, Telangana, India and the four checks *viz*., M 35-1, Paiyur 2, AKJ 1 and GS 23. This experiment was conducted during *rabi*, 2021, in an augmented design at the College of Agriculture, Raichur, Karnataka, India, receiving an annual average rainfall of 658 mm. Checks were repeated in four blocks with 100 genotypes. Each block was of 4 m length with a uniform spacing of 45 x 15 cm. Each genotype was sown in a single row. The recommended package of practices and necessary plant protection measures were taken to raise a healthy crop. The observations were recorded on days to 50% flowering, days to maturity, plant height, peduncle length, neck of panicle, panicle length, panicle width, panicle weight per plant, 100-grain weight, grain yield per plant and the biochemical parameters carbohydrate, protein and minerals (Fe and Zn) were estimated after the harvest of the crop. The carbohydrate content was estimated by following the Anthrone method (Hedge and Hofreiter, 1962) and the protein content by the Kjeldahl method.

The micronutrient content of the sorghum genotypes, iron (Fe) and zinc (Zn), were estimated by atomic absorption spectrometry (AAS) with zinc and iron hollow cathode lamps (Jackson, 1973). The digested material with suitable dilutions was aspirated into an AAS flame and the concentration of Fe and Zn was recorded in ppm by referring to the standard curve. The Fe and Zn concentrations were calculated using the following formula.

$$\text{Micronutrient}\left(\text{Zn and Fe}\right)\left(\frac{\text{mg}}{\text{Kg}}\right)=\frac{\text{Concentration}\times\ \text{Volume ofextract}}{\text{Weight of sample}}$$

Grain yield per plant was subjected for statistical analysis as per the augmented design in Indostat software. The data of biochemical parameters was subjected for analysis of descriptive statistics (mean, maximum, minimum, range, standard deviation and variance).

The correlation among the grain yield and biochemical parameters and graphs were worked out in Excel. The cluster analysis was carried out in R software and constructed the dendrogram.

Results and Discussion

The maximum number of genotypes studied were from Yemen (46) followed by Cameroon (24) and Sudan (12). Among the different pericarp-colored grain sorghum types, the majority of genotypes contained red color pericarp (36). Only two check varieties, M35-1 and GS 23, are white color. The mean data of protein content, Fe and Zn, along with grain yield per plant, was represented in Table 1.

Table 1: Mean, range, variance of carbohydrate, protein, Fe and Zn content with grain yield of colored sorghum genotypes

Sl. No.	Descriptive statistics	Carbohydrate (%)	Protein (%)	Iron (Fe) (mg/kg)	Zinc (Zn) (mg/kg)	Grain yield per plant (g)
1	Mean	69.28	8.86	38.92	28.31	52.25
2	Minimum	45.46	4.00	19.51	8.36	9.58
3	Maximum	82.00	20.10	59.54	51.11	120.00
4	Range	36.54	16.10	40.03	42.75	110.42
5	Standard error	0.64	0.31	0.90	0.96	2.36
6	Standard deviation	6.53	3.11	9.18	9.83	24.11
7	Variance	42.64	9.68	84.36	96.68	581.36

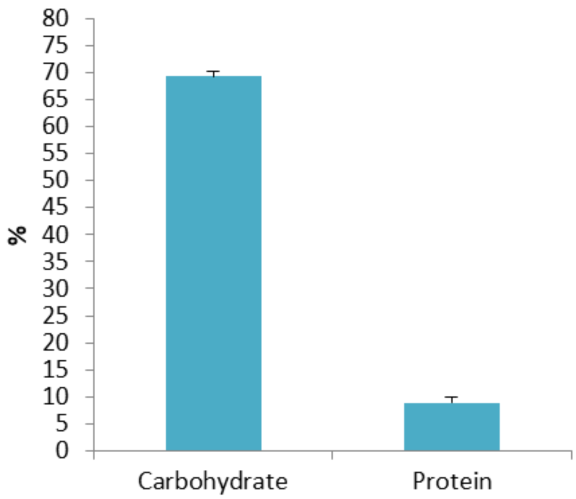

Figure 1: Protein and carbohydrate content with standard error

Carbohydrate Content (%)

Sorghum, a climate-resilient cereal crop known for its drought tolerance, has gained interest as a potential bioenergy feedstock and for its nutritional benefits (Paterson *et al*., 2009). Investigating the genetic diversity within sorghum is essential for harnessing its full potential, particularly regarding carbohydrate and protein content (Paterson *et al*., 2009). The carbohydrate content in sorghum grains ranges from 54.6 to 85.2% (Osman *et al*., 2022). But in this study, the carbohydrate content across various genotypes exhibited a notable range, ranging from 45.46 to 82.00%, with an average value of 69.21% (Table 1 and Figure 1). Among these, the genotype IS 14897 (Red) recorded the lowest carbohydrate content (45.46%), while IS 522 (Purple) showed the highest content (82 %) followed by genotype IS 22942 (Reddish Brown), which contained 80.24% (Table 2). In comparison, the check genotype GS-23 showed 74.23% of carbohydrate content. Among tested various genotypes, 21 genotypes surpassed the carbohydrate levels of GS-23, indicating a promising potential for higher yield varieties. This trend aligns with the previous research conducted by Kavitha (2018), who reported the carbohydrate content in 50 genotypes of sorghum ranged from 55.55 to 72.27% and Suvarna (2019) reported the range of carbohydrate content of 64.2 to 82.9% in the landraces of sorghum studied. Kiran (2021) reported this in the range of 47.18 to 86.47 in 25 genotypes with different pericarp colors and Kallanagouda (2023) reported the range from 51.49 to 75.89%.

Furthermore, when examining the different colored grains, the most significant variation in carbohydrate content was observed in the purple grains, followed by the red grains (Table 3). This suggests that color may play a role in the nutritional profile of these genotypes, suggesting a further investigation into their potential applications in agriculture and food science.

Protein Content (%)

The protein content of various genotypes ranged from 4.0 to 20.10%, with an average of 8.87% (Table 1). Notably, the IS 32072 (Purple) genotype exhibited the highest protein content of 20.10%, followed by IS 14897 (Red) with 17.70% protein content (Table 3 and Figure 2). In contrast, the IS 28244 (Red) genotype had the lowest protein content of 4.0%. Among the control varieties, GS-23 had a relatively high protein content of 11.68%. Previous studies have reported protein content in various ranges: 5.44 to 12.90% (Neucere and Sumrell, 1980), 4.40 to 21.10% (Jambunathan *et al*., 1981), 6.80 to 19.60% (Subramanian *et al*., 1990), 10.00 and 14.00% (Awadelkareem, 2002 and Awadelkareem *et al*., 2009), 9.7 to 16.3% (Nguni *et al*., 2012), 8.08 to 15.26% (Shegro *et al*., 2012), 7.9 to 12.5% (Suvarna, 2019), 8.20 to 16.47% (Tasie *et al*., 2020), 3.11 to 20.3% (Kiran, 2021) and 4.49 to 15.12% (Kallanagouda, 2023). The protein content is influenced by both genotype and environmental factors during the growing seasons, as noted by Benzian *et al*., (1983) and Ebadi *et al*., (2005). Among the different colored grains, purple grains showed the highest protein content, followed by red and reddish-brown varieties (Table 3 and Figure 2). This suggests a greater variation in protein content within the purple grain category compared to red. Notably, 16 genotypes exhibited protein levels exceeding that of the best check variety, GS-23 (Table 4). The energy required for producing high-protein grains is significantly greater than that for low-protein grains. For instance, 1 g of glucose is estimated to yield 0.83 g of grain storage carbohydrates but only 0.49 and 0.67 g of storage proteins (Singh, 2012). Consequently, increasing protein content is often incompatible with enhanced yield unless total photosynthesis is proportionately increased. This aligns with the current study's findings, where out of 16 colored genotypes, only four—IS 28065, IS 31706, IS 28049, and IS 23890—demonstrated higher grain yields alongside elevated protein content compared to the best check, GS-23. Recent research has further explored the adaptability and stability of protein content across different genotypes. For example, a study by Araujo *et al*., (2022) used GGE biplot analysis to evaluate the adaptability of cowpea genotypes for protein content, highlighting the importance of both genetic and environmental factors in determining protein levels in grains. Additionally, Tanin *et al*., (2022) conducted a genetic analysis of grain protein content, grain yield and thousand-kernel weight in bread wheat, emphasizing the complex interactions between these traits.

Micronutrient (Fe and Zn) Content (mg/kg)

The iron (Fe) content of the sorghum genotypes in this study ranged from 19.51 to 59.94 mg/kg, with an average concentration of 39.20 mg/kg (Table 1 and Figure 3). The

Table 2: Carbohydrate, protein, Fe and Zn content and grain yield per plant of colored grain sorghum genotypes with their country origin

S. No.	*Genotype*	*Country source*	*Grain color*	*Carbohydrate (%)*	*Protein (%)*	*Fe (mg/kg)*	*Zn (mg/kg)*	*Grain yield per plant (g)*
1	IS 522	Mexico	Purple	82.0	4.8	26.4	15.5	26.9
2	IS 2502	United States of America	Brown	70.3	10.5	53.3	42.4	43.7
3	IS 2582	United States of America	Brown	73.0	4.7	38.8	27.9	85.9
4	IS 2618	United States of America	Purple	71.0	7.2	52.2	41.2	74.7
5	IS 3579	Sudan	Purple	76.2	7.9	33.1	22.2	49.5
6	IS 3817	Mali	Purple	77.6	7.2	49.6	38.6	26.0
7	IS 6508	India	Brown	74.5	9.4	36.7	25.8	119.2
8	IS 7013	Sudan	Red	75.9	9.2	39.3	28.4	29.1
9	IS 7527	Nigeria	Reddish brown	77.2	6.6	26.6	15.7	44.4
10	IS 8222	Uganda	Purple	73.3	5.6	44.8	33.9	25.0
11	IS 8792	Zimbabwe	Purple	71.0	7.4	30.1	19.2	32.6
12	IS 9664	Sudan	Purple	80.0	8.9	41.2	30.3	20.6
13	IS 11180	Ethiopia	Red	71.0	6.8	56.6	45.7	9.6
14	IS 12643	Ethiopia	Purple	59.5	9.6	33.1	22.2	60.0
15	IS 14897	Cameroon	Red	45.5	17.7	43.3	32.4	25.1
16	IS 14904	Cameroon	Brown	78.6	5.2	46.7	35.8	49.2
17	IS 14905	Cameroon	Reddish brown	69.3	8.4	47.5	36.6	39.0
18	IS 15098	Cameroon	Reddish brown	71.8	8.5	50.8	39.9	35.2
19	IS 16006	Cameroon	Brown	66.3	5.5	48.7	37.8	113.8
20	IS 16169	Cameroon	Red	66.0	6.8	43.0	32.1	32.5
21	IS 16202	Cameroon	Brown	73.8	10.9	36.0	24.2	29.6
22	IS 16310	Cameroon	Purple	71.0	7.3	33.5	22.2	62.0
23	IS 16316	Cameroon	Reddish brown	73.7	4.5	37.2	25.4	24.6
24	IS 16398	Cameroon	Reddish brown	75.5	4.8	36.6	24.9	81.1
25	IS 17591	Yemen	Red	65.7	5.0	24.2	12.8	42.9
26	IS 18301	Niger	Reddish brown	71.3	8.9	45.2	33.9	21.3
27	IS 18639	Nigeria	Brown	68.3	7.7	22.5	11.1	70.6
28	IS 18679	U.S.A	Purple	73.5	8.8	40.4	29.1	25.3
29	IS 19298	Sudan	Brown	73.8	7.6	34.7	23.3	41.5
30	IS 19299	Sudan	Reddish brown	63.4	10.4	23.9	12.5	54.4
31	IS 21868	Yemen	Brown	70.2	5.5	40.1	28.3	14.2
32	IS 22436	Sudan	Red	55.7	6.1	42.4	31.0	40.2
33	IS 22897	Sudan	Reddish brown	74.0	7.9	34.7	23.3	60.2
34	IS 22942	Sudan	Reddish brown	80.2	6.9	32.3	21.0	45.8
35	IS 19498	Sudan	Brown	64.3	7.8	56.1	44.7	66.1
36	IS 20301	Niger	Purple	68.0	10.9	36.0	24.6	52.5
37	IS 20842	U.S.A	Red	66.7	11.2	37.1	25.7	55.5
38	IS 21835	Sudan	Reddish brown	70.3	16.1	28.1	17.1	55.4
39	IS 23890	Yemen	Reddish brown	56.7	12.6	33.4	22.3	94.9
40	IS 23916	Yemen	Red	71.3	9.2	53.9	42.8	31.6
41	IS 40175	Mauritania	Brown	62.4	8.2	34.4	21.6	20.0

42	IS 22949	Sudan	Reddish brown	68.3	5.4	32.7	21.7	50.5
43	IS 22970	Sudan	Reddish brown	64.0	8.3	24.0	12.9	11.4
44	IS 23864	Yemen	Red	66.6	13.5	45.6	34.6	63.4
45	IS 23865	Yemen	Red	72.1	7.5	59.5	48.5	89.5
46	IS 28000	Yemen	Brown	65.7	11.4	29.7	18.7	59.0
47	IS 28001	Yemen	Brown	70.7	8.5	35.6	13.6	32.4
48	IS 28009	Yemen	Brown	55.3	12.2	48.7	37.6	31.1
49	IS 28014	Yemen	Reddish brown	65.7	7.5	33.9	22.7	36.7
50	IS 23954	Yemen	Red	53.0	7.8	48.2	51.1	63.1
51	IS 23955	Yemen	Red	74.5	7.4	36.7	26.2	80.0
52	IS 24001	Yemen	Red	70.3	7.8	43.0	31.9	58.4
53	IS 28056	Yemen	Brown	61.0	12.6	24.5	13.5	41.0
54	IS 28065	Yemen	Red	73.0	15.4	36.8	25.7	102.9
55	IS 28074	Yemen	Brown	73.3	6.1	25.6	15.2	69.7
56	IS 28172	Yemen	Reddish brown	71.7	6.6	36.5	26.1	43.3
57	IS 28015	Yemen	Red	67.7	7.6	33.0	22.6	44.4
58	IS 28017	Yemen	Reddish brown	74.4	6.8	38.0	28.3	65.4
59	IS 28049	Yemen	Purple	54.3	13.4	42.5	32.8	94.3
60	IS 28050	Yemen	Red	73.0	10.2	26.4	16.7	39.4
61	IS 28217	Yemen	Red	75.0	6.2	38.9	29.2	75.1
62	IS 28224	Yemen	Brown	72.0	10.8	39.6	29.9	76.8
63	IS 28230	Yemen	Brown	70.0	5.3	38.1	28.4	60.9
64	IS 28176	Yemen	Red	64.3	6.4	37.8	28.0	70.4
65	IS 28198	Yemen	Red	71.0	9.5	37.7	28.0	71.0
66	IS 28200	Yemen	Red	73.0	10.0	50.1	40.4	83.6
67	IS 28202	Yemen	Red	75.0	9.2	36.9	27.2	87.9
68	IS 28237	Yemen	Brown	61.3	5.4	43.9	34.2	71.3
69	IS 28244	Yemen	Red	69.0	4.0	47.6	37.9	43.7
70	IS 28250	Yemen	Red	50.5	12.6	36.0	26.2	33.6
71	IS 28265	Yemen	Purple	70.0	10.3	39.1	29.4	25.8
72	IS 28792	Yemen	Red	66.0	5.5	32.8	23.1	39.3
73	IS 28966	Yemen	Purple	59.7	7.7	54.4	44.7	32.8
74	IS 29031	Yemen	Red	72.3	11.0	57.7	48.0	88.0
75	IS 28982	Yemen	Purple	75.0	9.8	51.7	40.6	30.1
76	IS 29012	Yemen	Red	63.8	8.4	40.8	29.6	36.0
77	IS 29013	Yemen	Red	74.8	11.8	22.9	11.8	66.0
78	IS 29032	Yemen	Purple	59.7	13.2	47.9	36.8	120.0
79	IS 29033	Yemen	Red	65.0	12.4	41.3	30.2	69.4
80	IS 29052	Yemen	Reddish brown	62.0	14.6	38.1	27.5	68.0
81	IS 31706	Yemen	Red	74.7	14.2	50.4	39.2	86.5
82	IS 30722	Cameroon	Brown	73.0	4.8	43.2	32.1	29.1
83	IS 30736	Cameroon	Brown	63.0	5.4	45.3	34.1	45.7
84	IS 30754	Cameroon	Brown	73.7	5.6	48.6	37.5	32.9
85	IS 30800	Cameroon	Reddish brown	69.0	10.0	46.2	35.0	45.3
86	IS 30802	Cameroon	Brown	75.3	4.6	38.7	27.5	34.6
87	IS 30781	Cameroon	Red	65.3	11.6	35.0	23.9	47.9

88	IS 31906	Yemen	Red	77.3	9.2	36.0	27.5	55.0
89	IS 32072	Yemen	Purple	67.3	20.1	47.0	50.8	24.7
90	IS 32165	Yemen	Purple	70.7	6.3	42.9	31.7	12.6
91	IS 32185	Yemen	Purple	71.0	8.9	53.8	42.7	34.7
92	IS 33158	Cameroon	Reddish brown	77.9	5.1	20.6	9.4	44.0
93	IS 33159	Cameroon	Brown	72.0	10.6	26.0	14.8	58.0
94	IS33310	Cameroon	Red	61.7	5.0	19.5	8.4	47.0
95	IS33317	Cameroon	Red	70.7	10.7	43.7	32.5	48.0
96	IS 33323	Cameroon	Red	71.7	4.8	19.8	8.7	65.8
97	IS 33336	Cameroon	Red	73.0	9.8	31.2	23.5	74.9
98	IS 33343	Cameroon	Red	66.0	13.6	27.7	16.6	40.4
99	IS 34723	Cameroon	Reddish brown	72.0	10.9	28.1	16.9	58.0
100	IS 35642	Chad	Reddish brown	65.7	9.7	45.3	34.1	17.7
	Check varieties							
101	M-35-1	India	White	72.3	10.5	36.0	24.5	72.4
102	AKJ-1	India	Red	73.0	11.0	38.3	28.9	68.6
103	Paiyur 2	India	Red	71.0	11.2	39.0	29.0	56.7
104	GS-23	India	White	74.2	11.7	46.8	38.3	78.1

Table 3: Mean, range and variance for protein, carbohydrate, Fe and Zn and grain yield per plant in different color grain genotypes

S. No.	*Parameter*	*Pericarp color*	*No. of genotypes*	*Mean*	*Max.*	*Min.*	*Range*	*Standard error*	*S.D.*	*Variance*
1	Carbohydrate (%)	Brown	24	69.25	78.6	55.3	23.3	1.15	5.66	32.00
		Purple	19	70.04	82.0	54.3	27.7	1.69	7.35	54.04
		Red	38	68.21	77.3	45.5	31.9	1.16	7.17	51.46
		Reddish brown	21	70.20	80.2	56.7	23.6	1.27	5.80	33.63
		White	2	73.27	74.2	72.3	1.9	0.97	1.36	1.86
2	Protein (%)	Brown	24	7.76	12.6	4.6	8.0	0.55	2.67	7.13
		Purple	19	9.23	20.1	4.8	15.3	0.80	3.47	12.04
		Red	38	9.40	17.7	4.0	13.7	0.51	3.17	10.05
		Reddish brown	21	8.59	16.1	4.5	11.6	0.67	3.08	9.50
		White	2	11.07	11.7	10.5	1.2	0.62	0.87	0.76
3	Fe (mg/kg)	Brown	24	38.98	56.1	22.5	33.6	1.86	9.10	82.72
		Purple	19	42.09	54.4	26.4	28.0	1.93	8.43	71.04
		Red	38	39.21	59.5	19.5	40.0	1.59	9.80	95.98
		Reddish brown	21	35.22	50.8	20.6	30.3	1.83	8.38	70.21
		White	2	41.37	46.8	36.0	10.8	5.39	7.62	58.00
4	Zn (mg/kg)	Brown	24	27.50	44.7	11.1	33.6	1.96	9.62	92.50
		Purple	19	32.03	50.8	15.5	35.3	2.20	9.59	91.98
		Red	38	29.10	51.1	8.4	42.8	1.68	10.36	107.33
		Reddish brown	21	24.15	39.9	9.4	30.5	1.84	8.44	71.23
		White	2	31.39	38.3	24.5	13.8	6.89	9.74	94.81
5	Grain yield per plant (g)	Brown	24	54.00	119.2	14.2	104.9	5.50	26.95	726.45
		Purple	19	43.68	120.0	12.6	107.4	6.40	27.92	779.42
		Red	38	56.89	102.9	9.6	93.3	3.48	21.43	459.41
		Reddish brown	21	47.44	94.9	11.4	83.5	4.44	20.37	414.88
		White	2	75.22	78.1	72.4	5.7	2.83	4.00	16.02

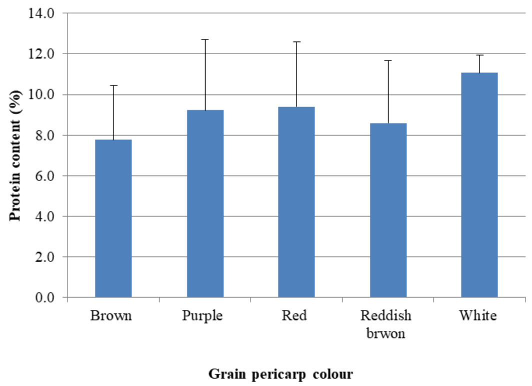

Figure 2: Mean protein content in different grain pericarp colour in sorghum

Table 4: List of colored sorghum genotypes containing high protein content compared to best check variety GS 23

S. No.	*Genotype*	*Grain color*	*Protein (%)*	*Grain yield per plant (g)*
1	IS 32072	Purple	20.10	24.68
2	IS 14897	Red	17.70	25.08
3	IS 21835	Reddish brown	16.10	55.38
4	IS 28065	Red	15.40	102.88
5	IS 29052	Reddish brown	14.60	68.00
6	IS 31706	Red	14.20	86.48
7	IS 33343	Red	13.60	40.38
8	IS 23864	Red	13.50	63.38
9	IS 28049	Purple	13.40	94.28
10	IS 29032	Purple	13.20	120.00
11	IS 23890	Reddish brown	12.60	94.88
12	IS 28056	Brown	12.60	41.00
13	IS 28250	Red	12.60	33.58
14	IS 29033	Red	12.40	69.38
15	IS 28009	Brown	12.20	31.08
16	IS 29013	Red	11.80	66.00
	Check variety			
	GS-23	White	11.68	78.05

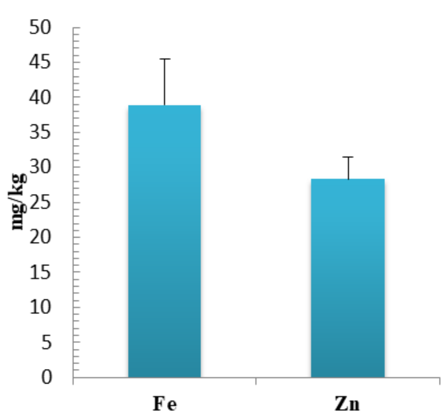

Figure 3: Fe and Zn content in coloured grain sorghum genotypes

genotype IS 23865 (Red) exhibited the highest Fe content at 59.54 mg/kg, closely followed by IS 29031 (Red) at 57.69 mg/kg (Table 2). Conversely, IS 33310 (Red) displayed the lowest Fe content at 19.51 mg/kg. Among the check varieties, GS-23 recorded the highest Fe content at 46.75 mg/kg.

The zinc (Zn) content varied from 8.36 to 51.11 mg/kg, with a mean of 28.31 mg/kg (Table 1 and Figure 3). The genotype IS 23954 (Red) showed the highest Zn content at 51.11 mg/kg, followed by IS 32072 (Red) at 46.98 mg/kg (Table 2). Again, IS 33310 (Red) had the lowest Zn content at 8.36 mg/kg. Among the check varieties, GS-23 recorded the highest Zn content at 38.27 mg/kg, followed by Paiyur 2 (28.99 mg/kg) and AKJ-1 (28.86 mg/kg) (Table 2).

Similarly, variations among genotypes for grain Fe and Zn contents were reported. Kumar *et al.,* (2010) reported that Fe content among the genotypes varied from 29.8 to 44.2 mg/kg and grain Zn content from 22.2 to 32.9 mg/kg, whereas Fe content ranged from 28 mg/kg to 63 mg/100 g and grain Zn content ranged 23 to 55 mg/kg by Nguni *et al.,* (2012). Badigganavar *et al.* (2016) reported that grain iron and zinc content ranged from 11 to 95 mg/kg and 11 to 75 mg/kg, respectively, in the germplasm lines. Hariprasanna *et al.*, (2012) reported that grain Fe content varied among genotypes, with values ranging from 28.9 to 34.9 mg/kg, while Zn content ranged from 20.4 to 25.7 mg/kg in diverse sorghum accessions, highlighting the potential for biofortification efforts in sorghum breeding programs. Kallanagouda (2023) reported the Fe and Zn content in the range of 29.97 to 58.10 mg/kg and 21.15 to 50.48 mg/kg, respectively. Kayode *et al.*, (2006) documented an average Fe concentration of 58 mg/kg, with a range of 30 to 113 mg/kg, and a Zn concentration ranging from 11 to 44 mg/kg, with an average of 25 mg/kg across various varieties. They noted that the highest concentrations were found in red-colored genotypes, emphasizing the significance of color in nutrient content. The variation in Fe and Zn content was more pronounced in red-colored grains, followed by brown-colored grains (Table 3 and Figure 4). Greater variation in Zn content was also observed among

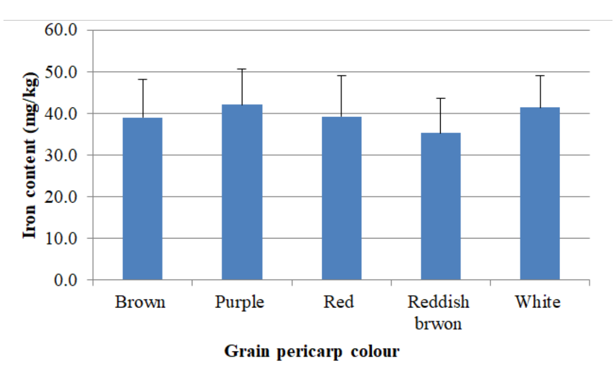

Figure 4: Mean iron content (mg/kg) in different grain pericarp coloured genotypes in sorghum

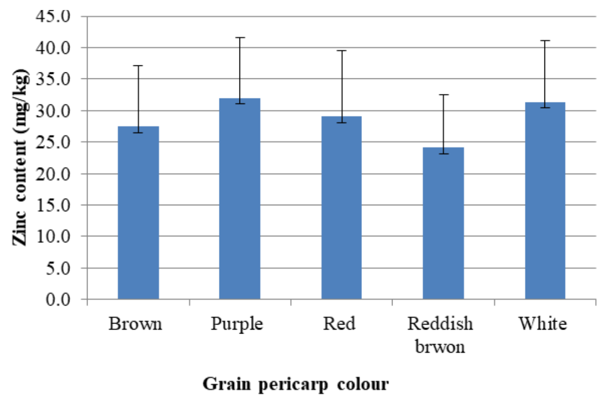

Figure 5: Mean zinc content (mg/kg) in different grain pericarp coloured genotypes in sorghum

Table 5: List of colored sorghum genotypes containing high iron and zinc content compared to best check variety GS 23.

Sl. No.	Genotype	Grain color	Iron (mg/kg)	Zinc (mg/kg)	Grain yield per plant (g)
1	IS 23954	Red	48.178	51.11	63.08
2	IS 32072	Purple	46.978	50.83	24.68
3	IS 23865	Red	59.538	48.47	89.48
4	IS 29031	Red	57.688	47.98	87.98
5	IS 11180	Red	56.598	45.68	09.58
6	IS 28966	Purple	54.418	44.71	32.78
7	IS 19498	Brown	56.058	44.69	66.08
8	IS 23916	Red	53.848	42.78	31.58
9	IS 32185	Purple	53.808	42.66	34.68
10	IS 2502	Brown	53.268	42.35	43.68
11	IS 2618	Purple	52.148	41.23	74.68
12	IS 28982	Purple	51.738	40.59	30.08
13	IS 28200	Red	50.118	40.41	83.58
	Check variety				
	GS-23	White	46.75	38.27	78.05

red-colored grains, followed by white, brown, and brown-purple (Table 3 and Figure 5). The genotypes exhibiting the highest Fe and Zn contents are listed in Table 5. Factors such as growing season and soil characteristics significantly influenced the mineral composition and protein content of sorghum genotypes. Zhang *et al*., (2010) indicated that both environmental conditions and genotype interactions play critical roles in determining micronutrient content in crops. Furthermore, Shegro *et al*., (2012) highlighted that the final grain composition is influenced by genotype differences, soil mineral concentrations, and environmental factors throughout the growth period.

Correlation Among the Characters

Correlations between characters are of great importance for the success of selection practiced in breeding programs. In the present study, grain yield per plant was not correlated with any biochemical parameters studied, indicating that there is no penalty for enhancing grain protein, Fe, and Zn concentration in the present material under study, and it is possible to develop high protein, Fe and Zn lines with higher grain yield (Table 6). Among the biochemical parameters, protein is negatively correlated with carbohydrate content (r = -0.3216), and grain Fe is significantly and positively correlated with grain Zn (r = 0.9216) content (Figure 6), indicating that either the genetic factors for Fe and Zn contents are linked, or the physiological mechanisms were interconnected for Fe and Zn uptake and translocation in the grain. Similar results were reported by Reddy *et al.* (2010), Ashokkumar *et al.* (2012) and, Andiku *et al*. (2022), Kallanagouda (2023) for Fe and Zn. However, grain Zn concentrations in sorghum are governed predominantly by additive gene effects, suggesting the high effectiveness of progeny selection in pedigree selection or population breeding to develop lines with increased levels of grain Zn concentrations, while the grain Fe concentrations is governed predominantly by non-additive gene effects in combination with additive gene effects, suggesting scope for heterosis breeding in addition to progeny selection to develop lines with increased levels of grain Fe concentrations (Kumar *et al.,* 2013 and Gaddameedi *et al.,* 2020). In order to realize the potential impact of micronutrient-dense cultivars, micronutrients must be delivered in high-yielding backgrounds with farmers' preferred traits importantly acceptable seed color and large seed size.

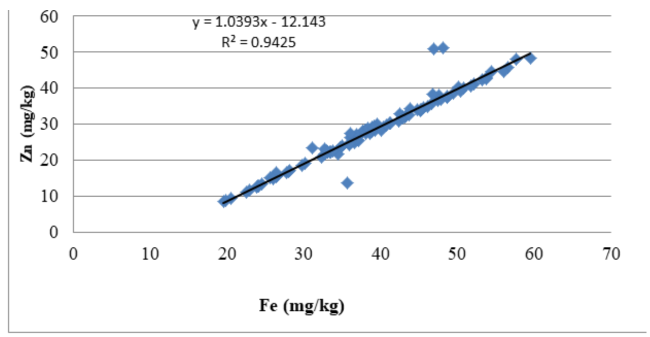

Figure 6: Correlation between iron and zinc content (mg/kg)

Correlation of Protein, Fe and Zn with Other Morphological Characters and Yield Related Characters

Both Fe and Zn minerals were negatively correlated with days to 50% flowering (-0.209 and -0.203, respectively) and positively correlated with plant height (0.274 and 0.333), peduncle length (0.319 and 0.290), neck of panicle (0.277 and 0.253), panicle length (0.297 and 0.288). Selection for high Fe and Zn content grain genotypes can be selected based on the above characters. Protein was not correlated with any of the morphological and yield-related characters (Table 7). Similar studies were conducted by Kallanagouda (2023),

Table 6: Correlation of grain yield per plant along with protein, iron and zinc

Character	Carbohydrate (%)	Protein (%)	Fe (mg/kg)	Zn (mg/kg)	GYPP (g)
Carbohydrate (%)	1.0000	-0.3216**	-0.0660	-0.0984	-0.0037
Protein (%)		1.0000	0.0611	0.1108	0.1666
Fe (mg/kg)			1.0000	0.9708**	0.0111
Zn (mg/kg)				1.0000	0.0306
GYPP (g)					1.0000

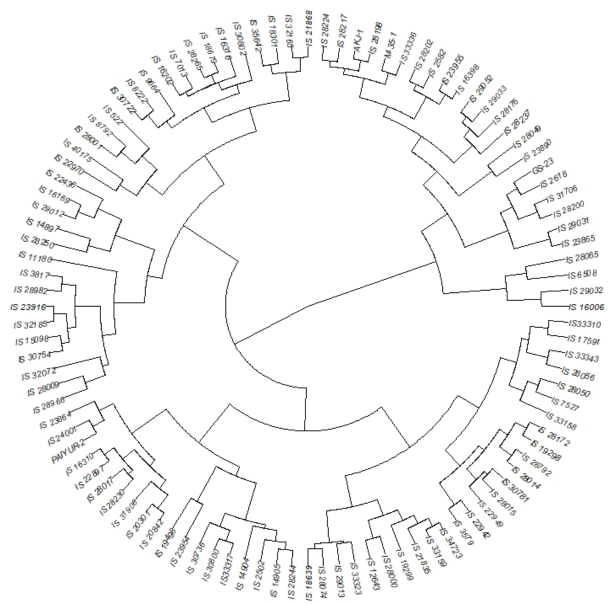

Figure 7: Cluster diagram depicting two main clusters based on carbohydrate, protein, iron and zinc and grain yield in sorghum

who reported that both Fe and Zn were positively correlated with days to 50% flowering and plant height and negatively correlated with reported grain yield and 100 grain weight. Only Fe was negatively correlated with days to maturity.

Cluster Analysis

Using software R, cluster analysis was carried out for all the genotypes studied and constructed the dendrogram.

Table 7: Correlation of morphological and yield parameters with protein, Fe and Zn content in sorghum

S. No.	*Character*	*Protein (%)*	*Fe (mg/kg)*	*Zn (mg/kg)*
1	Days to 50% flowering	-0.029	-0.209*	-0.203*
2	Days to maturity	-0.067	0.100	0.093
3	Plant height (cm)	0.069	0.274**	0.333**
4	Peduncle length (cm)	-0.041	0.319**	0.290**
5	Neck of panicle	-0.005	0.277**	0.253**
6	Panicle length	0.088	0.297**	0.288**
7	Panicle width (cm)	0.009	0.140	0.150
8	Panicle weight per plant (g)	0.148	-0.026	-0.001
9	Hundred grain weight (g)	-0.032	0.109	0.125
10	Grain yield per plant (g)	0.167	0.011	0.031

All the genotypes were clustered into two major clusters based on five characters Fe, Zn, protein, carbohydrate and grain yield per plant (Figure 7). The one cluster consists of 26 genotypes, in which the checks M-35-1, AKJ 1 and GS 23 were present and the remaining 78 genotypes belongs to another group. This group contains Paiyur 2. Andiku *et al*. (2022) studied cluster analysis among 348 genotypes based on phenotypic traits and Fe and Zn contents and the genotypes were grouped into four clusters. This helps in the selection of genotypes with high Fe and Zn-containing groups as donors for developing biofortified varieties in sorghum.

Conclusion

The presence of a considerable amount of compositional variability of mineral and protein contents among tested genotypes suggests that they can be a valuable source of genes for the nutritional quality improvement of sorghum. Understanding the mechanisms of micronutrient uptake and translocation is crucial for enhancing grain quality. Identifying the genetic basis for these traits, including the mapping of relevant genes and linked markers, is essential for the effective genetic dissection and manipulation of complex traits in sorghum and other crops. This knowledge will facilitate the development of sorghum varieties with improved nutritional profiles, addressing micronutrient deficiencies in vulnerable populations.

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