



Research article

Genetic variability and correlation analysis for improving grain yield and fodder quality in dual-purpose sorghum (*Sorghum bicolor* L.)

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Abstract

Sorghum (*Sorghum bicolor*), a dual-purpose crop, helps bridge the feed gap and integrate crop-livestock systems, especially in places with significant forage deficiencies. To address the need for superior dual-purpose sorghum lines with improved fodder quality and high grain production, this study evaluated 121 sorghum lines during *kharif* 2022 in Ludhiana and Faridkot, Punjab, India, using an alpha lattice design to assess genetic variability, heritability, and trait correlations among agro-morphological and quality traits. High ($\geq 80\%$) genotypic and phenotypic coefficients of variation were observed for traits such as number of tillers/plant, 100-grain weight, and plant height, with high heritability (broad sense) observed for 100-grain weight and flavonoids (mg/g) content. The identification of high-performing lines like SCL4, ICS 14334, IS 8282, SL 44, SSV 84, and SCL 2, which combine high crude protein content ($>8.0\%$) and increased grain production (>650 g/plot), highlights the potential of developing dual-purpose sorghum lines with improved nutritional and yield characteristics. Significant positive correlations were observed between crude protein (CP) and growth parameters, including leaf width, plant height, and dry matter yield (DMY). Furthermore, DMY was significantly associated with flavonoids and starch, underscoring the intricate balance between nutrient uptake, biomass production, and protein synthesis. These findings provide a strong foundation for breeding programs aimed at improving both production and nutritional quality in forage sorghum, addressing the growing need for sustainable dual-purpose crops.

Keywords: Fodder, Genetic variability, Grain, Sorghum, Yield

Introduction

In the harsh environments of the tropics and semi-arid zones, raising healthy livestock is a complex challenge. While many factors play a role, the shortage of quality feed and the growing struggle for available land stand out as major hurdles that directly impact animal health and productivity. Marginal farmers, who rely on livestock for economic security, often depend on low-nutrient crop residues during lean seasons. Poor nutrition directly reduces livestock productivity, including milk yield, growth rate, and reproductive performance, ultimately affecting farmers' livelihoods and income. Over the past decade, efforts to improve crops have focused on the development of dual-purpose cultivars in response to these problems. These crops maximize both grain yield and biomass quality, offering a sustainable solution for small-scale mixed farming systems by optimizing limited land and water resources (Somegowda *et al.*, 2021;

Shafiqurrahman *et al.*, 2024). In a recent study, Santhiya *et al.* (2026) identified forage and grain type sorghum accessions after characterizing 132 sorghum germplasm. Sorghum (*Sorghum bicolor* (L.) Moench) has emerged as a vital solution for these challenges, owing to its inherent drought tolerance, dual-purpose utility, and resilience in marginal soils. Valued for its rapid growth habit and superior nutritional profile, sorghum is cultivated as a fodder crop to improve livestock productivity (Chaithrashree *et al.*, 2024). It provides high dry matter and green fodder yields, often outperforming maize under water-limited conditions (Schittenhelm and Schroetter, 2014; Getachew *et al.*, 2016).

Ensuring a continuous supply of green fodder throughout the year is crucial for sustaining livestock productivity and reducing the cost of milk production (Mahanta *et al.*, 2020). The total area under fodder crops in India is merely 5% of the cultivable area, while the recommendation is

at least 10% (Gupta *et al.*, 2020). With rapid urbanization and industrialization limiting the scope for expanding cultivation areas, it is imperative to increase forage productivity per unit area. In order to increase the production of forage crops per unit area and meet the demands for fodder, it is necessary to find forage sorghum lines with wider adaptability and high-yielding potential. However, developing superior genotypes requires a focus on both yield and nutritional quality (Tokas *et al.*, 2021). In order to accomplish this, it is necessary to broaden the base of genetic variability, followed by the selection of promising lines that have higher yields with improved nutritional quality. Analyzing genetic parameters is crucial, as the magnitude of genetic variability and the distance between parental lines guide the selection process and the achievement of heterosis (Abu-Ellail *et al.*, 2023). The creation of genetically diverse populations is fundamental to crop improvement, enabling the effective selection of superior yield and nutritional traits. Sorghum exhibits extensive variability owing to its broad environmental adaptability. To harness this potential, understanding the associations between morphological and quality traits is pivotal for simultaneous improvement. Consequently, developing dual-purpose cultivars that combine high dry matter and grain yields with superior nutritional quality is essential to address the critical feed shortages constraining livestock production. Therefore, the present study evaluates the genetic variability parameters and examines correlations among agro-morphological and quality traits in sorghum lines. These findings are intended to support the breeding of superior genotypes that combine high grain and fodder production along with superior fodder quality.

Materials and Methods

Study site and experimental design: An experimental trial comprising 121 sorghum lines was conducted in an alpha lattice design with two replications during *kharif* 2022 at two locations, namely Punjab Agricultural University, Ludhiana and Regional Research Station, Faridkot. Each genotype was sown in paired rows, maintaining a row-to-row spacing of 45 cm and plant-to-plant spacing of 15 cm. The recommended package of practices was followed to ensure uniform and healthy crop growth. For recording observation, three plants were randomly selected from each plot for plant-based traits. Data were recorded on the following agro-morphological traits, namely, flag leaf length (cm), flag leaf width (cm), plant height (cm), number of tillers/plant, days to 50% flowering, and 100-grain weight (g). In addition, dry matter yield (kg/plot) and grain yield (g/plot) were recorded on a plot basis. Days to 50% flowering were recorded based on visual observation and defined as the

number of days from sowing until 50% of the plants in a plot reached anthesis.

Estimation of quality traits: The quality parameters were carried out at the 'Fodder quality lab', PAU, Ludhiana. The whole sorghum plants, including leaves and stems, were collected at the 50% flowering stage for quality analysis. The crude protein (%), crude fiber (%), crude fat, starch (mg/g), ash content (%) and nitrogen-free extracts (%) were estimated as per AOAC (1995). Tannins (mg/100g) were extracted from the powdered sorghum samples and quantified following the methodology outlined by Sadasivam and Manickam (1992). A colorimetric reaction was developed using Folin-Denis reagent, and absorbance was measured at 700 nm. A standard curve was prepared using tannic acid (10–100 µg) as a reference, and the tannin content was calculated and expressed as tannic acid equivalents. In addition, total phenols (mg/g), flavonoids (mg/g) and flavonols (mg/g) were estimated as per Swain and Hills (1959) methodology.

Statistical analysis: Statistical analysis was performed using R Software version 4.0.3 (RStudio 2020) with the 'agricolae' (de Mendiburu and Yaseen, 2020) R package. Data were subjected to analysis of variance (ANOVA), and genotypic and phenotypic coefficients of variation, heritability, and Pearson's correlation coefficients were also calculated.

Results and Discussion

Analysis of variance for morphological and quality traits: The analysis of variance (ANOVA) revealed significant ($P \leq 0.05$) differences among sorghum genotypes for all morphological, yield, and quality traits at both Ludhiana and Faridkot, as well as in the pooled analysis (Table 1-2), indicating the presence of substantial genetic variability. A similar pattern of significance was observed across both locations for most traits, including plant height, days to 50% flowering, 100-grain weight, grain yield, crude protein, and flavonoid content, suggesting relatively stable expression and strong genetic control. However, some differences in the magnitude of variation were evident between locations. Morphological traits such as leaf length, grain yield, and dry matter yield showed relatively greater variability at Ludhiana, whereas traits like leaf width and certain quality parameters, including total phenols and ash content, exhibited comparatively higher variation at Faridkot. In contrast, traits such as number of tillers per plant, 100-grain weight, flavonoids, and crude protein displayed a more consistent pattern across both environments, indicating their relative stability.

The pooled analysis further revealed significant genotype × location interactions for most traits, suggesting that the performance of certain genotypes was influenced by

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Table 1. Analysis of variance (ANOVA) for morphological traits in sorghum lines

Source of variation	df	Leaf length (cm)	Leaf width (cm)	No. of tillers plant ⁻¹	Plant height (cm)	Days to 50% flowering	100-grain weight (g)	Dry matter yield (kg plot ⁻¹)	Grain yield (g plot ⁻¹)
Ludhiana									
Genotype (adj.)	120	64.91**	1.27**	0.90**	1340.88**	91.09**	0.41**	0.31**	11848.00**
Replication	1	20.44	1.42	0.00	241.92	3.57	0.12	0.10	66476.00
Blocks within reps (adj.)	20	24.99	0.27	0.08	129.19	9.42	0.01	0.21	2311.00
Error	100	26.21	0.28	0.05	217.09	14.67	0.01	0.18	1909.00
Faridkot									
Genotype (adj.)	120	116.85**	1.09**	0.94**	1129.66**	72.18**	0.39**	0.27**	5634.00**
Replication	1	7.89	2.51	0.19	981.28	184.80	0.01	7.96	83825.00
Blocks within reps (adj.)	20	15.11	0.29	0.04	165.20	6.95	0.01	0.17	1785.00
Error	100	31.12	0.18	0.07	114.86	16.17	0.01	0.16	1741.00
Across locations									
Location	1	0.76	6.27**	1.72**	170.31	618.46**	7.38**	3.40**	8899.00*
Rep (location)	2	14.17	1.96	0.10	611.60	94.19	0.07	4.03	75151.00
Blk (loc × rep)	40	20.05	0.27	0.06	147.20	8.18	0.01	0.19	2048.00
Genotype	120	147.50**	2.01**	1.29**	2045.25**	151.06**	0.57**	0.38**	13916.00**
Loc × Genotype	120	14.17**	0.35**	0.55**	425.30**	12.21**	0.23**	0.19**	3566.00**
Error	200	28.66	0.23	0.06	165.97	15.42	0.01	0.17	1825.00

* Significant at 5% level; ** Significant at 1% level; df = Degree of freedom

Table 2. Analysis of variance (ANOVA) for quality traits in sorghum lines

Source of variation	df	TP	FL	FD	TAN	CP	CF	CFi	ST	NFE	Ash
Ludhiana											
Genotype (adj.)	120	0.34**	0.35**	0.52**	3.34**	0.94**	0.32**	8.42**	39.97**	12.63**	0.84**
Replication	1	0.03	0.04	0.00	0.02	0.53	0.02	9.29	5.84	8.19	0.32
Blocks within reps (adj.)	20	0.05	0.01	0.01	0.14	0.21	0.01	2.67	18.66	2.67	0.06
Error	100	0.02	0.01	0.01	0.14	0.15	0.01	2.38	8.16	1.81	0.03
Faridkot											
Genotype (adj.)	120	0.41**	0.35**	0.31**	1.72**	0.91**	0.23**	8.73**	32.36**	10.60**	0.97**
Replication	1	0.00	0.01	0.01	0.81	0.01	0.06	180.66	9.31	183.73	0.24
Blocks within reps (adj.)	20	0.02	0.01	0.01	0.11	0.11	0.02	4.41	19.23	3.93	0.09
Error	100	0.02	0.02	0.01	0.10	0.07	0.01	4.48	7.78	4.07	0.12
Across locations											
Location	1	6.12**	1.37**	13.59**	72.27**	0.07	0.06*	434.53**	20.56	237.89**	35.32**
Rep (loc)	2	0.02	0.02	0.01	0.42	0.27	0.04	85.31	8.53	95.96	0.28
Blk (loc × rep)	40	0.04	0.01	0.01	0.13	0.16	0.02	3.21	18.53	3.30	0.08
Genotype	120	0.47**	0.41**	0.55**	2.84**	1.38**	0.39**	8.89**	49.07**	14.35**	1.00**
Loc × Genotype	120	0.28**	0.28**	0.28**	0.42**	0.48**	0.17**	6.95**	20.56**	8.89**	0.81**
Error	200	0.02	0.01	0.01	0.12	0.11	0.01	3.19	8.09	2.94	0.08

*Significant at 5% level; ** Significant at 1% level; df = Degree of freedom; TPH: Total phenols (mg g⁻¹); FL: Flavonols (mg g⁻¹); FD: Flavonoids (mg g⁻¹); TAN: Tannins (mg 100 g⁻¹); CP: Crude protein (%); CF: Crude fat (%); CFi: Crude fibre (%); ST: Starch (mg g⁻¹); NFE: Nitrogen free extracts (%); Ash: Ash content (%)

environmental conditions, particularly for traits like dry matter yield, tannins, and starch. The observed variation between locations may be attributed to differences in agro-climatic conditions such as soil fertility, temperature, and moisture availability. Overall, the presence of substantial genetic variability along with genotype × environment interaction highlights the importance of multi-location evaluation for identifying stable and high-performing dual-purpose sorghum genotypes with improved grain yield and fodder quality. Sarshad *et al.* (2021) and Navya *et al.* (2021) also observed significant variation among sorghum genotypes for quality traits such as crude protein, crude ash, phenol, flavonoids, and antioxidant content. Likewise, Gebergergs and Mekbib (2020) reported significant variability among sorghum genotypes for important agronomic traits, including days to flowering, plant height, panicle length, and grain yield.

Mean performance for morphological and quality traits: The assessment of genetic parameters, including variability estimates such as range, mean, genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), and heritability in the broad sense (%), was recorded (Table 3). Significant morphological variation was evident among the sorghum lines at both the Ludhiana and Faridkot locations. At Ludhiana, plant height exhibited substantial diversity, averaging 165.3 cm; SSV 74 was the tallest genotype (223.6 cm), while IS 8029 was the shortest (95.9 cm). In terms of phenology, the days to 50% flowering spanned from 58 days (HBL 16) to 94 days (IS 8414), with an average of 74.8 days. Productivity traits also showed marked variability: grain yield fluctuated between 501.4 g/plot (GGUB 50) and a maximum of 841.5 g/plot (ICS 14334), averaging 616.9 g/plot. Other morphological traits included leaf length, which averaged 69.6 cm (ranging from 54.7 cm in EC 33 to 82.4 cm in ELG 3), and 5.3 cm (IS 7873) to 10.4 cm (ICS 323) for leaf width. Conversely, traits such as 100-grain weight (1.3–3.2 g), dry matter yield (5.4–7.4 kg/plot), and tillers/plant (1.2–4.5) displayed comparatively narrower ranges of variation. A comparable trend was observed at the Faridkot location. Plant height averaged 164.8 cm, with genotype SL 44 recording the maximum (216.5 cm) and IS 7788 the minimum (106.5 cm). Leaf length and grain yield averaged 69.7 cm and 608.3 g/plot, respectively. Similar to Ludhiana, moderate variability was recorded for days to 50% flowering (mean 72.5 days) and dry matter yield (mean 6.1 kg/plot). The number of tillers/plant (averaged 2.6), ranging from 1.4 (ICS 52) to 4.4 (IC 249096), while 1.4 (IS 7788) to 3.7 g (EB 1) for 100-grain weight. Across both environments, the genotypes SCL 4, IS 8282, CSV 24SS, ICS 14334, and SSV 84 consistently demonstrated superior grain yields, underscoring their potential for inclusion in future breeding programs. A broad range of trait values for grain yield, panicle length and seed index has also been reported in sorghum by Somu *et al.* (2025),

who demonstrated that traits such as panicle length and weight have a direct contribution to grain yield. In an earlier study, Verma *et al.* (2025) reported the effect of zinc application on growth and nutritional parameters of fodder sorghum.

Substantial variability in quality traits was observed across both locations (Table 4), indicating pronounced differences in the nutritional quality of the evaluated genotypes. Significant variation was observed for key nutritional characteristics at Ludhiana. Crude protein content ranged from 5.4% (IS 7663) to 9.2% (ICSB 94012), while starch content varied between 51.6 mg/g (GGUB 64) and 76.3 mg/g (SCL 2). The range of nitrogen-free extracts, which represent digestible carbohydrates, was 51.4% (E 197) to 63.2% (GGUB 32). Ash content, an indicator of mineral composition, ranged from 4.0% (E 228) to 7.0% (ICSV 717) and crude fibre from 23.1 (GGUB 32) to 31.8% (PEC 5). Similarly, at Faridkot, crude protein content varied from 6.0% (IS 7017) to 9.2% (IS 8282), 48.4 mg/g (GGUB 56) to 72.5 mg/g (SSV 17) for starch content and 53.5% (HBL 24) to 64.5% (GGUB 50) for nitrogen-free extracts. Ash content at Faridkot ranged from 4.1%

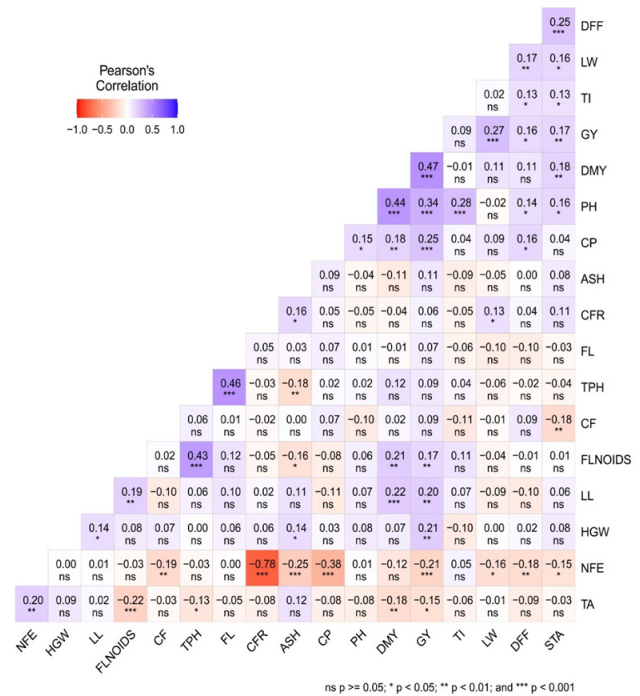


Fig 1. Correlation plot for measuring association between measured traits of different sorghum lines (LL: Leaf length; LW: Leaf width; TI: Number of tillers/plant; PH: Plant height; DFF: Days to 50% flowering; HGW: 100-Grain weight; DMY: Dry matter yield; GY: Grain yield; TPH: Total phenols; FL: Flavonols; FLNOIDS: Flavonoids; TA: Tannins; CP: Crude protein; CFR: Crude fibre; CF: Crude fats; STA: Starch; ASH: Ash content; NFE: Nitrogen free extracts).

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Table 3. Genetic variability parameters for morphological traits of sorghum lines

Trait	Range	Mean	PCV (%)	GCV (%)	ECV (%)	Heritability (%)
Ludhiana						
Leaf length (cm)	54.70-82.40	69.60	9.60	6.10	7.40	40.30
Leaf width (cm)	5.30-10.40	7.50	11.80	9.50	7.00	65.10
Number of tillers plant ⁻¹	1.2-4.5	2.70	25.90	24.60	8.20	89.90
Plant height (cm)	95.9-223.6	165.30	16.20	13.90	8.50	72.50
Days to 50% flowering	59.0-94.0	74.80	10.10	8.70	5.10	74.40
100-grain weight (g)	1.3-3.2	2.40	19.10	18.60	4.10	95.40
Dry matter yield (kg plot ⁻¹)	5.4-7.4	6.30	7.80	3.50	6.90	20.90
Grain yield (g plot ⁻¹)	501.4-841.5	616.90	13.20	11.10	7.30	69.90
Faridkot						
Leaf length (cm)	47.6-82.3	69.70	12.20	9.60	7.60	61.50
Leaf width (cm)	5.0-9.6	7.30	11.00	9.10	6.10	69.00
Number of tillers plant ⁻¹	1.4-4.4	2.60	27.80	25.80	10.10	86.70
Plant height (cm)	106.5-232.2	164.80	14.60	13.10	6.50	80.20
Days to 50% flowering	59-86	72.50	9.40	7.70	5.30	67.80
100-grain weight (g)	1.4-3.7	2.60	17.10	16.70	3.70	95.40
Dry matter yield (kg plot ⁻¹)	5.2-7.1	6.10	7.40	3.50	6.50	22.50
Grain yield (g plot ⁻¹)	495.3-775.7	608.30	10.00	7.20	6.90	52.20

PCV: Phenotypic coefficient of variation; GCV: Genotypic coefficient of variation; ECV: Environmental coefficient of variation; h² : Heritability (broad sense)

Table 4. Genetic variability parameters for quality traits of sorghum lines

Traits	Range	Mean	PCV (%)	GCV (%)	ECV (%)	h ² (%)
Ludhiana						
Total phenols (mg/g)	1.7-3.8	2.70	16.0	14.9	6.0	85.9
Flavonols (mg/g)	1.0-2.9	1.70	24.3	23.7	5.4	95.1
Flavonoids (mg/g)	1.0-3.2	1.80	28.2	27.5	6.2	95.2
Tannins (mg/100g)	4.2-9.8	6.60	20.0	19.1	5.7	92.0
Crude protein (%)	5.4-9.2	7.70	9.7	8.1	5.3	70.5
Crude fat (%)	1.2-3.1	1.90	22.0	21.3	5.4	94.0
Crude fibre (%)	23.1-31.8	27.90	8.3	6.2	5.6	55.2
Starch (mg/g)	51.6-76.3	60.80	6.4	5.2	5.2	60.3
Ash content (%)	4.0-7.0	5.40	12.2	11.7	3.6	91.1
NFE (%)	51.4-63.2	57.10	4.7	4.0	2.4	73.2
Faridkot						
Total phenols (mg/g)	1.3-3.3	2.50	18.8	18.0	5.5	91.3
Flavonols (mg/g)	1.0-2.8	1.80	23.3	22.2	7.1	90.7
Flavonoids (mg/g)	1.0-2.6	1.50	26.8	26.4	4.9	96.6
Tannins (mg/100g)	5.0-9.5	7.40	12.9	12.2	4.3	88.8
Crude protein (%)	5.9-9.5	7.60	9.2	8.5	3.7	84.1
Crude fat (%)	1.1-2.5	1.80	19.1	18.2	6.2	89.6
Crude fibre (%)	23.5-36.1	28.10	9.2	5.1	7.6	30.4
Starch (mg/g)	48.4-72.4	60.40	7.5	5.4	5.2	52.2
Ash content (%)	4.1-7.5	6.10	12.3	11.0	5.6	79.3
NFE (%)	53.5-64.2	58.60	4.6	3.1	3.4	44.7

PCV: Phenotypic coefficient of variation; GCV: Genotypic coefficient of variation; ECV: Environmental coefficient of variation; h² : Heritability (broad sense); NFE: Nitrogen free extract

(GGUB 64) to 7.5% (IS 8166) and for crude fibre, it ranged from 23.5% (GGUB 55) to 36.1% (HBL 24). These results demonstrate considerable variability in key nutritional traits and highlight the potential for selecting genotypes with superior nutritional profiles to enhance forage quality and digestibility.

Antinutritional traits also exhibited considerable variability across locations. At Ludhiana, tannin content ranged from 4.2 mg/100g (ICS 444) to 9.8 mg/100g (PEC 7), total phenols from 1.7 mg/g (GGUB 55) to 3.8 mg/g (IS 8036), flavonols from 1.0 mg/g (SSV 17) to 2.9 mg/g (ICSV 745), and flavonoids from 1.0-3.2 mg/g. At Faridkot, tannin content ranged from 5.1 mg/100g (IS 7017) to 9.5 mg/100g (IS 8282), total phenols varied between 1.3 mg/g (ICSB 2077) and 3.4 mg/g (EA 11), flavonols from 1.0 mg/g (HBL 3) to 2.8 mg/g (IS 7873) and flavonoids from 1.0-2.6 mg/g. These compounds are known to play a crucial role in plant defense mechanisms; however, their elevated levels may reduce palatability and nutrient availability. Similar variability in phenolic compounds has been reported by Dykes and Rooney (2006), highlighting their dual role in contributing to antioxidant activity while influencing nutritional quality. Overall, the observed variability for morphological and quality traits highlights the potential for selecting superior genotypes that combine high yield with improved nutritional quality. Such genotypes can be effectively utilized in breeding programs aimed at developing dual-purpose sorghum cultivars suitable for both grain and fodder purposes.

Genetic variability and heritability of morphological and quality traits: For all morphological traits, the phenotypic coefficient of variation (PCV) was higher than the genotypic coefficient of variation (GCV), suggesting the influence of environmental factors on their expression (Table 3). Similar results were reported earlier by Dalip *et al.* (2024) and Akshitha *et al.* (2024). At Ludhiana, the phenotypic and genotypic coefficients of variation (PCV and GCV) were highest for the trait like number of tillers/plant (25.9; 24.6), followed by 100-grain weight (19.1; 18.6) and plant height (16.2; 13.9). Similarly, at Faridkot, the highest values were observed for the number of tillers/plant (27.8; 25.8), followed by 100-grain weight (17.1; 16.7), plant height (14.6; 13.1), leaf length (12.2; 9.6), leaf width (11.0; 9.1), days to 50% flowering (9.9; 7.7), and dry matter yield (7.4; 3.5). These findings align with Subramanian *et al.* (2019) and Jimmy *et al.* (2017), who identified tillering as a high-plasticity trait essential for biomass recovery in dual-purpose systems. The narrow differences between PCV and GCV for traits like plant height and grain weight suggest relative resistance to environmental fluctuations, which might be influenced by factors including temperature, relative humidity, soil type, and soil health between Ludhiana and Faridkot. Moreover, it indicates the presence of adequate genetic

variability, enhancing the likelihood of effective selection. Consequently, the top-performing lines identified in this study are likely to remain stable across different regions. Furthermore, the high variability observed in leaf width and length is consistent with the findings of Kumar *et al.* (2020) and Singh *et al.* (2016), confirming that breeders can effectively enhance fodder quality by selecting for superior leaf architecture. However, estimation of GCV and PCV alone is insufficient to predict the heritable fraction. Combining these coefficients with heritability and expected genetic advance provides a better understanding of selection potential. Singh (2001) states that a heritability estimate is considered low (<40%), moderate (40–80%), and high ($\geq 80\%$). In this study, heritability was highest for 100-grain weight (95.4) at both locations, followed by the number of tillers/plant (89.9 at Ludhiana and 89.7 at Faridkot) and plant height (80.2 at Faridkot). Days to 50% flowering (74.4), plant height (72.5), grain yield (69.9), leaf width (65.1), and leaf length (40.3) all showed moderate heritability values at Ludhiana, while at Faridkot, moderate heritability was noted for days to 50% flowering (67.8), grain yield (52.2), leaf width (69.0), and leaf length (61.5). Low heritability estimates were recorded for dry matter yield (20.9 at Ludhiana and 22.5 at Faridkot), likely due to the non-additive nature of the trait or significant environmental influence, suggesting that selection for this trait may not be highly effective. These results highlight the potential for improving traits with high heritability and genetic variability through targeted breeding programs. The significant variability observed for phenological traits like days to 50% flowering and maturity aligns with the findings of Sushil (2014) and Tariq *et al.* (2012), who noted that such diversity is essential for adapting sorghum to varying terminal stress conditions. Gebergergs and Mekbib (2020) recorded high to moderately high heritability for plant height, days to 50% flowering and grain yield. Also, moderate to high heritability was observed for leaf breadth and green fodder yield in the study represented by Kumar *et al.* (2020), suggesting additive gene action and effective selection.

The estimation of genotypic and phenotypic coefficients of variation (GCV and PCV) for quality traits, as presented in Table 4, reveals distinct patterns of variability across locations. At Ludhiana, the highest values were recorded for flavonoids (27.5; 28.2) and flavonols (23.7; 24.3), followed by crude fat (21.3; 22.0), tannins (19.1; 20.0), and total phenols (14.9; 16.0). The wide genetic base for these antioxidant compounds is biologically significant, as they are primary drivers of host-plant resistance to biotic stresses. According to Dicko *et al.* (2005), phenols and flavonoids in sorghum leaves and stems are subject to intense evolutionary pressure to defend against foliar pathogens and pests, which explains why they maintain higher genetic variation than primary macronutrients. In

contrast, lower variability was observed for ash content (11.7; 12.2), crude protein (8.1; 9.7), and crude fibre (6.2; 8.3), with starch (5.2; 6.4) and nitrogen-free extract (4.0; 4.7) showing the least variation. A similar trend was evident at Faridkot, where flavonoids (26.4; 26.8) and flavonols (22.2; 23.3) again exhibited the maximum variation. Significant estimates were also noted for crude fat (18.2; 19.1) and total phenols (18.0; 18.8). Moderate to low estimates were recorded for the remaining traits, including tannins (12.2; 12.9), ash content (11.0; 12.3), and crude protein (8.5; 9.2). Consistent with the Ludhiana location, crude fiber, starch, and nitrogen-free extract at Faridkot displayed minimal variability, with values ranging from 3.1 to 9.2 across parameters. The success of selecting a particular trait relies not solely on the amount of genetic variation present in the base material, but also on how effectively that variation can be passed on from one generation to the next generation (Johnson *et al.*, 1955). At Ludhiana, high heritability (% broad sense) was observed for traits like flavonoids (95.1) followed by flavonols (95.1), crude fat (94.0), tannins (92.0), ash content (91.1), total phenols (85.9) and moderate heritability was observed for nitrogen free extracts (73.2), crude protein (70.5), starch (60.3) and crude fibre (55.2). While at Faridkot, it was highest for flavonoids (96.6) followed by total phenols (91.3), flavonols (90.7), crude fat (89.6), tannins (88.8), crude protein (84.1); moderate heritability observed for ash content (79.3), starch (52.2), nitrogen-free extracts (44.7); and low heritability for crude fiber (30.4).

Correlation analysis of morphological and quality traits: Pearson's correlation analysis of agro-morphological traits was conducted (Fig 1). This analysis helps to identify key traits and guides selection strategies for improving desirable characteristics in sorghum. The analysis revealed that DMY exhibited a highly significant positive correlation with plant height ($r = 0.48, p < 0.001$), leaf length ($r = 0.22, p < 0.001$) and grain yield ($r = 0.47, p < 0.001$), while the number of tillers/plant was shown to be negatively and non-significantly correlated with DMY. The positive association between plant height and DMY indicates that taller plants possess greater photosynthetic surface area, which improves light interception and increases assimilate production, ultimately leading to a higher accumulation of aboveground biomass. These trends are consistent with findings by Kumar and Singh (2012), Jain and Patel (2013) and Deshmukh *et al.* (2018), who noted that for dual-purpose sorghum, selection based on height and leaf area is more effective for total biomass gain than selection based on tillering capacity. Grain yield showed a highly significant positive correlation with dry matter yield ($r = 0.47, p < 0.001$) and plant height ($r = 0.37, p < 0.001$) and leaf width ($r = 0.28, p < 0.001$). Furthermore, positive associations were identified with 100-grain weight ($r = 0.21, p < 0.01$), leaf length ($r = 0.20, p < 0.01$) and days to 50% flowering ($r = 0.16, p < 0.01$). These

findings highlight the importance of selecting for traits such as plant height, leaf dimensions, and flowering time to improve both grain yield and dry matter yield in sorghum.

The correlation analysis of quality traits revealed that antioxidant parameters, specifically total phenols, are strongly co-dependent with flavonols ($r = 0.46, p < 0.001$) and flavonoids ($r = 0.43, p < 0.001$). A high degree of inter-connectivity between total phenols, flavonols, and flavonoids indicates a shared phenylpropanoid metabolic pathway (Dykes and Rooney, 2006). These compounds act as a unified defense system where the plant allocates carbon resources to specific phenolic branches based on environmental stress. Interestingly, a significant negative correlation between total phenols and tannins ($r = -0.13, p < 0.05$) was observed, suggesting a potential metabolic redirection where the plant prioritizes immediate antioxidant response over long-term chemical defense. Crude fiber showed a positive correlation with ash content ($r = 0.16, p < 0.05$), indicating a potential link between structural components and mineral composition. Crude fiber, on the other hand, showed a highly significant negative correlation with nitrogen-free extracts ($r = -0.78, p < 0.001$), suggesting an inverse relationship between digestible carbohydrates and fiber content. Starch content demonstrated a positive correlation with crude fiber ($r = 0.11, p < 0.05$), while a negative correlation was observed with nitrogen-free extracts ($r = -0.15, p < 0.05$).

Correlation study between agro-morphological and quality traits also revealed that the leaf width, plant height, DMY and grain yield showed positive correlation with the crude protein. The identification of fodder lines with the highest crude protein content is crucial for selecting superior quality fodder varieties. High crude protein is a critical parameter for forage quality, contributing to improved milk and meat production in ruminants. The lines that showed high crude protein content along with high grain yield include SCL 4, ICS 14334, IS 8282, SL 44, SSV 84 and SCL 2. This positive relationship between plant growth parameters like leaf width, plant height, dry matter yield and crude protein content underscores the intricate balance between nutrient uptake, biomass production, and protein synthesis in forage sorghum, indicating a potential avenue for improving both yield and nutritional quality in forage sorghum. Dry matter yield showed a positive correlation with flavonoids and starch. While leaf width showed a positive correlation with crude fiber and starch. An optimal amount of fiber content is necessary to maintain high-quality forage crops, but exceeding this threshold leads to a decline in forage quality (Abdi and Habibi, 2017), which depends on the genotype and on the stage of harvest for fodder use. The quality of forage directly impacts digestive processes, the need for supplemental concentrates, animal performance, and overall health. So, the correlation analysis will help the

breeder in the simultaneous improvement of all these traits to develop a superior quality fodder.

Conclusion

This study confirms significant genetic diversity among the 121 sorghum lines evaluated, providing a robust basis for dual-purpose crop improvement. High genetic variability (GCV and PC) and strong broad-sense heritability (>80%) for traits like 100-grain weight and flavonoid content indicate high potential for selection. The analysis revealed different clusters based on performance for various traits, with certain genotypes standing out for their superior characteristics. Notably, lines such as SCL 4, ICS 14334, IS 8282, SL 44, SSV 84, and SCL 2, which effectively balanced high crude protein (> 8.0%) and grain production (> 650 g/plot) coupled with favorable quality traits like total phenols, flavonoids, and low antinutritional factors. These genotypes exhibit a balance between high nutritional quality and yield potential, which aligns well with the criteria for dual-purpose systems. Furthermore, the significant positive correlations between crude protein and growth parameters ($r = 0.16$, $p < 0.05$) demonstrate that biomass and nutritional quality can be improved simultaneously. The prevalence of significant genetic variability, high heritability, and strong correlations among key traits such as leaf width, plant height, grain yield, and crude protein underscores the potential for simultaneous improvement of these quality traits. The identification of high-performing genotypes and the understanding of trait relationships provide a robust foundation for breeding programs aimed at developing elite sorghum cultivars with enhanced fodder and grain quality. In order to meet the increasing demand for sustainable crop-livestock integration, these findings emphasize the importance of integrating desirable traits into breeding lines to create high-yielding, nutritionally enriched sorghum varieties appropriate for dual-purpose systems.

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