



Fodder and grain yield potential of little millet (*Panicum sumatrense* Roth ex Roem. & Schult.) race *robusta* and identification of trait-specific germplasm for crop improvement

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Abstract Little millet is one of the small millets native to India, used for both food and fodder purposes. Among the two races (*nana* and *robusta*) of little millet, race *robusta* has a robust growth habit and produces high biomass and grain yield but matures late compared to race *nana*. In this study, 126 accessions belonging to the race *robusta* conserved in the ICRISAT Genebank were evaluated during two rainy seasons for fodder and grain yield potential, for the identification of trait-specific germplasm for little millet improvement. Residual maximum likelihood analysis revealed significant variability for all traits evaluated in the individual seasons and pooled for the two seasons. High heritability was observed for most traits in the individual seasons and the pooled data for the two seasons. Principal component analysis revealed the existence of genetic diversity and identified the key traits that contributed to maximum variability. Cluster analysis revealed two major clusters that could form the basis for selecting diverse

genotypes for breeding programs. Based on the pooled data, the top 20 accessions each for high grain yield and fodder yield (stover dry weight) were identified, of which accessions IPmr 880, IPmr 871, IPmr 875, IPmr 896 and IPmr 907 were identified for dual purposes (grain and fodder), whereas accessions IPmr 702, IPmr 873, IPmr 876, IPmr 913, and IPmr 1056 were the top five in terms of stover dry weight yield. Multi-location testing of identified sources for yield and adaptation and their use in breeding programs aids in little millet improvement and cultivar releases.

Keywords Little millet · Landraces · Germplasm · Biomass · Grain Yield

Introduction

The rapid increase in the global population and the increasing impact of climate change on various crops pose a significant threat to global food and nutritional security. Global crop cultivation is dominated by cereals such as rice, wheat, and maize, which account for around 40% of the total area under cultivation (FAO 2025). Crop diversification, which can result in better soil health and the development of sustainable agroecosystems (Yang et al. 2020), therefore, it is a need of the day. Diverse crops with better climate resilience and nutritional richness can help combat threats to food and nutritional security. Small millets are crops with greater endurance to biotic and abiotic

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stresses and nutritional superiority, but they are currently considered underutilized. To transform food systems into diverse, sustainable, climate-resilient, and able to meet our nutritional requirements, there is a need for the cultivation of underutilized but climate-resilient and nutrient-dense crops, making them an integral part of our food basket.

Little millet (*Panicum sumatrense* Roth ex Roem. & Schult.) is one of the small millets, belonging to the family Poaceae. It is cultivated as a cereal crop in India and is widely distributed as a weed or wild plant in many Asian countries, including Nepal, Pakistan, Sri Lanka, Indonesia, and Myanmar (Vetriventhan et al. 2020). India is the largest producer of the little millet with an area of 0.26 million ha and a productivity of 0.12 million tons (Bhat et al. 2018). In India, it is grown primarily in the tribal belts of Madhya Pradesh, Chhattisgarh, and Andhra Pradesh and Tamil Nadu (Nandini et al. 2019). Little millet has high water-use efficiency and salt and waterlogging tolerance, and is less prone to insect pests and diseases (Upadhyaya et al. 2016; Ganapathy 2017; Vetriventhan et al. 2021). Several investigations have revealed the nutraceutical richness of little millet in terms of carbohydrates, protein, and phenols, and it is particularly rich in iron (18–58 mg/kg), zinc (19–40 mg/kg), calcium (92–390 mg/kg), protein (6–16%), and dietary fibre (7.7%) (Saleh et al. 2013; Longvah 2017; Vetriventhan et al. 2021). It can easily substitute for rice-based recipes and is considered a functional and nutritional food choice for the management of diet-related metabolic disorders (Mannuramath et al. 2015). The acceptance of little millet-based products, such as *dosa*, and *pongol* and more by people and their preference over meals prepared from polished white rice envisages future scope (Anitha et al. 2024).

The productivity of little millet remains low because it is largely cultivated on marginal lands under rainfed conditions with minimal inputs and crop improvement efforts. Furthermore, rice and wheat straw (21.9 and 15.1%, respectively) are the dominant dry feed stocks for the ruminants in India (Duncan et al. 2020). Identifying crops with better forage potential, in addition to grain yield, is essential for promoting crop diversification. Identification of little millet with high grain yield and greater fodder potential can establish it as a better candidate for crop diversification. Focusing on genetic diversity

and its estimation is essential for the success of plant breeding programs. Among the two races of little millet, race *robusta* is a late maturing, erect culm with a large, strongly branched robust growth habit, and inflorescences are either erect and open (subrace *laxa*), or compact and curved (subrace *compacta*). While accessions belonging to the race *nana* produce plants with decumbent to almost all prostrate culms that become erect at flowering, produce erect, open strongly branched inflorescences (subrace *laxa*) or inflorescence branches that sometimes clump at the time of maturity (subrace *compacta*) (De Wet et al. 1983). Overall, race *nana* is early maturing, produces relatively low grain and biomass yields, and is prone to lodging, whereas race *robusta* is late maturing, mostly non-lodging, and produces higher grain and fodder yields than race *nana*. The greater yield potential of race *robusta* over *nana* and the trait-specific sources identified provide a greater scope for yield improvement (Vetriventhan et al. 2021). However, the forage potential of little millet remains largely unexplored. A study on the identification of trait-specific germplasm for high biomass revealed their potential (Vetriventhan et al. 2021) and emphasized the need for further research in this direction. There is a need for little millet cultivars with early maturity, non-lodging, high grain, and biomass yields. Currently, the ICRISAT Genebank conserves 473 accessions of little millet, including 126 accessions belonging to the race *robusta*, while the remaining accessions are of the race *nana*. The current study focused on the evaluation of a complete set of 126 little millet accessions of the race *robusta* and the identification of trait-specific sources for grain and fodder yields. This can strengthen little millet breeding programs and dietary diversification for food and fodder security and nutrition.

Materials and methods

Experimental material and details

The experimental material consisted of 126 accessions of the race *robusta*, which are conserved in the ICRISAT Genebank and four released cultivars (BL 6, GNV 3, GV 2 and Phule Ekadashi). All of them are landraces, originating from 10 states of India, the majority from Odisha (40), Andhra Pradesh

(39), Telangana (18) and Maharashtra (18) and remaining from Gujarat (3), Bihar (2), Tamil Nadu (2) and Rajasthan (1), with one unknown. The list of accessions along with passport data is included in Supplementary Table 1. The experiments were carried out in red soils during the 2021 and 2022 rainy seasons at the ICRISAT, Hyderabad, Telangana, India (17° 51' N latitude, 78° 27' E longitude, altitude 545 m above msl), using an alpha-lattice design with three replications. Sowing was done in a single row of 4 m length, row-to-row spacing of 60 cm, and plant-to-plant spacing of approximately 10 cm. Standard agronomic practices were followed during the crop growth period. The average rainfall at the experimental site over the last 10 years (2015–2024) was 1032 mm, varying from 568 to 1385 mm. The rainfall and temperature during the cropping season are presented in Table 1. Of the total annual rainfall during the cropping year, 75% and 81% of the rainfall were received during the cropping period (July–Dec) 2021 and 2022, respectively.

Data collection

Data were collected for 20 quantitative traits in both seasons. The traits, namely, days to 50% flowering, days to maturity, grain yield, stover fresh weight, and stover dry weight, were recorded on a plot basis, and grain yield, stover fresh weight, and stover dry weight were converted into kg/ha. The traits, namely plant height (cm), basal tillers per plant, flag leaf blade length (mm), flag leaf blade width (mm), flag leaf sheath length (mm), peduncle length (mm), panicle exertion (mm), inflorescence length (mm), inflorescence width (mm), inflorescence lowest primary branch length (mm), nodes per plant on main stalk,

leaves per plant on main stalk, culm thickness (mm) and 100 seed weight (g) were recorded on five randomly selected plants, and average values were calculated. The harvest index was calculated as the ratio of grain yield to biological yield (= grain yield + stover dry weight).

Statistical analysis

The data collected for 20 quantitative traits during both seasons were analysed individually and pooled over two seasons using the residual maximum likelihood (REML) approach in the GenStat 20th edition (VSN International 2022), considering genotypes as random and seasons as fixed for pooled analysis based on the following model, $y_{ijkl} = \mu + G_i + S_j + (GS)_{ij} + Rk_{(j)} + Bl_{(jk)} + \varepsilon_{ijkl}$.

where μ is the overall mean (constant), G_i is the effect of genotype i , S_j is the effect of season j , $(GS)_{ij}$ is the genotype \times season interaction for genotype i in season j , $Rk_{(j)}$ is the random effect of replication k nested within season j , $Bl_{(jk)}$ is the random effect of incomplete block l nested within replication k within season j , and ε_{ijkl} is residual error. The significance of seasons (fixed effects) was tested using Wald's statistics. The variance components of genotype (σ_g^2), genotype \times season (σ_{gs}^2), and error variance obtained through the analyses were used to calculate genetic parameters, such as heritability (h_b^2), genotypic and phenotypic coefficients of variation (GCV and PCV), genetic advance, and genetic advance as a percentage of the mean. The h_b^2 was categorized as low (<0.30), medium (0.30–0.60), and high (>0.60); while GCV and PCV values were categorized as low (<10%), medium (10–20%) and high (>20%) (Deshmukh et al. 1986). The genetic advance as % mean was categorised as low (<10%), medium (10–20%) and high (>20%) (Johnson et al. 1955). The best linear unbiased predictors (BLUPs) were estimated for various agronomic traits for individual and pooled seasons and were used for further analysis. The distribution of individual seasons was plotted using kernel density plots the using *ggplot2* package (version 3.5.1) of R software (<https://www.r-project.org/>). Correlation coefficients were estimated using the *metan* package (version: 1.18.0), and principal component analysis was performed using the package *factoextra*

Table 1 Rainfall and temperature details of the experiment site during the cropping season

Year	Rainfall (mm)		Temperature (°C) during the crop season (July–Dec)	
	Annual	Cropping season (July–Dec)	Minimum	Maximum
2021	1106	829	13.92–22.18	30.21–31.23
2022	1048	849	14.63–20.62	28.78–30.76

(version: 1.0.7) in R software. Hierarchical clustering was performed based on Euclidean distance and Ward's method using the libraries *Pandas* (McKinney 2011), *NumPy* (Walt et al. 2011), *Scikit-learn* (Pedregosa et al. 2011), *SciPy* (Jones et al. 2001) and *Matplotlib* (Hunter 2007) of the Python software. The trait-specific accessions for grain yield (kg/ha), stover fresh weight (kg/ha), and stover dry weight (kg/ha) were identified by comparing with better-performing checks (based on pooled BLUPs) for respective traits using LSD (5%).

Results

Variance components and heritability

The REML analysis indicated significant σ^2_g and σ^2_{gs} among the germplasm tested in the individual seasons and the pooled data of both seasons (Table 2). Wald's statistic for the season was highly significant for most traits, except plant height, flag leaf sheath length, inflorescence width and 100 seed weight. Overall, this study indicates the presence of significant variability among the accessions and the

Table 2 Variance components due to genotype (σ^2_g), genotype \times season interaction (σ^2_{gs}), and broad-sense heritability (h^2_b) for agronomic traits of little millet accessions evaluated in two rainy seasons (2021 and 2022) in ICRISAT, Patancheru, India

Trait	Individual season				Combined over two seasons			
	2021		2022		σ^2_g	σ^2_{gs}	Wald statistic season	h^2_b
	σ^2_g	h^2_b	σ^2_g	h^2_b				
Days to 50% flowering	88.29***	0.98	62.75***	0.97	71.76***	3.74***	153.90***	0.97
Days to maturity	93.67***	0.97	67.91***	0.97	76.16***	4.62***	171.85***	0.97
Plant height (cm)	366.50***	0.91	249.85***	0.79	292.53***	16.42***	0.63 ^{NS}	0.95
Basal tillers per plant	1.87***	0.69	1.46***	0.69	0.73***	0.94***	10.57*	0.55
Flag leaf blade length (mm)	319.87***	0.46	237.80***	0.37	217.30***	59.80***	101.83***	0.70
Flag leaf blade width (mm)	0.32***	0.28	0.54***	0.34	0.37***	0.06***	7.14*	0.67
Flag leaf sheath length (mm)	81.80**	0.56	76.85***	0.46	54.08***	25.03***	77.85 ^{NS}	0.81
Peduncle length (mm)	144.76***	0.41	100.17***	0.43	49.00***	73.40***	16.65*	0.43
Panicle exertion (mm)	207.19***	0.62	156.31***	0.82	105.18***	76.67***	20.02***	0.67
Inflorescence length (mm)	557.70***	0.65	272.25***	0.47	305.80***	107.00***	21.96***	0.75
Inflorescence width (mm)	305.63***	0.48	663.96***	0.69	298.90***	187.20***	1.06 ^{NS}	0.67
Inflorescence primary branch length (mm)	532.97***	0.71	624.85***	0.74	421.50***	159.50***	51.25***	0.78
Nodes per plant on main stalk	0.67***	0.73	0.19***	0.42	0.33***	0.10***	61.90***	0.78
Leaves per plant on main stalk	0.73***	0.73	0.18***	0.40	0.33***	0.12***	67.96***	0.76
Culm thickness (mm)	1.28***	0.74	0.58***	0.64	0.79***	0.14***	17.05*	0.86
100 Seed weight (g)	0.00043***	0.84	0.00041***	0.59	0.00038***	0.00004**	0.18 ^{NS}	0.88
Grain yield (Kg/ha)	77,044***	0.62	115,653***	0.75	35,096.00**	61,652.00***	281.13***	0.48
Stover fresh weight (Kg/ha)	38,892,452***	0.86	39,234,430***	0.95	34,444,783***	4,638,021***	16.77***	0.92
Stover dry weight (Kg/ha)	6,437,895***	0.83	4,161,279***	0.89	4,627,927***	690,204***	45.87***	0.91
Harvest Index	0.0045***	0.89	0.0034***	0.84	0.0033***	0.0006***	138.95***	0.89

*—Significant at $P \leq 0.05$, **—Significant at $P \leq 0.01$ and ***—Significant at $P \leq 0.001$; NS—non-significant

profound impact of the environment on the performance of accessions. Among the various traits, high heritability (>0.60) was observed for many traits during the 2021 and 2022 seasons and in the pooled data of both seasons. In the case of individual seasons, flag leaf blade length and flag leaf sheath length showed medium heritability (0.30–0.60), which was high when pooled, flag leaf blade width was low in 2021, medium in 2022, and high when pooled, and peduncle length was medium in both individual seasons and also in pooled. Basal tillers per plant showed high heritability in both individual seasons but medium when pooled. Inflorescence length, nodes per plant on the main stalk, leaves per plant on the main stalk and 100 seed weight showed high and medium heritability in 2021 and 2022 respectively and it was high when pooled. Medium heritability was observed in case of inflorescence width during 2021 and high in 2022 and pooled data. The remaining traits showed high heritability in individual seasons and pooled data of both seasons, with days to 50% flowering having the highest heritability among all traits, being 0.98 in 2021, 0.97 in both 2022 and the pooled data. The heritability of grain yield (kg/ha) was high in 2021 (0.62) and 2022 (0.75), but medium in the pooled case (0.48).

Mean, range and genetic variability parameters

The mean and range values of various traits were estimated from the pooled BLUPs, and the genetic parameters estimated using the variances are presented in Table 3. The distribution of genotypes for various traits during 2021 and 2022 can be observed from the kernel density (KDE) plot (Fig. 1). The greater values of PCV over GCV for all traits indicate the existence of an environmental influence, but the low margin between PCV and GCV shows that the influence was minimal. A high genetic advance as % mean ($>20\%$) was observed for most traits including days to 50% flowering, plant height (cm), basal tiller per plant, panicle exertion (mm), inflorescence primary branch length (mm), culm thickness (mm), stover fresh weight (kg/ha), stover dry weight (kg/ha), and harvest index, while low ($<10\%$) for flag leaf blade length and width (mm), and peduncle length (mm), and medium (10–20%) for days to maturity, flag leaf sheath length (mm), inflorescence length (mm), inflorescence width (mm), nodes per plant on

main stalk, leaves per plant on main stalk, grain yield (kg/ha) and 100 seed weight.

Correlation and trait contributions

Grain yield was positively correlated with days to 50% flowering, days to maturity, plant height (cm), flag leaf blade width (mm), peduncle length (mm), panicle exertion (mm), nodes per plant on main stalk, leaves per plant on main stalk, culm thickness (mm), stover fresh weight (kg/ha), and stover dry weight (kg/ha) (Fig. 2). Furthermore, a negative association was observed between grain yield (kg/ha) and traits such as basal tiller per plant, flag leaf sheath length (cm), inflorescence primary branch length (mm), and harvest index. The association with grain yield was non-significant for flag leaf blade length (mm), inflorescence length (mm), inflorescence width (mm), and 100 seed weight (g).

The direct and indirect effects of various traits on grain yield, estimated using path analysis, are presented in Supplementary Table 2. The positive correlations between grain yield and days to 50% flowering, plant height, panicle exertion, nodes per plant on main stalk and stover fresh weight were due to their positive direct effects. While positive associations between grain yield and days to maturity, culm thickness, leaves per plant on main stalk, flag leaf sheath length, peduncle length, and stover dry weight were observed due to the positive indirect effect. The negative correlations between grain yield, basal tiller per plant and 100 seed weight were due to direct negative effects. Indirect effects also contributed to the negative direct effects on inflorescence primary branch length.

Principal component analysis

PCA analysis revealed that the first four PCs (eigenvalue >1) together explained a variation of approximately 79.75% (Table 4). PC1 explained a large portion of the variability (45.11%), with an eigenvalue of 9.02. The traits, namely, nodes per plant on main stalk, leaves per plant on the main stalk, stover fresh weight, plant height, days to 50% flowering, days to maturity, culm thickness, stover dry weight and harvest index are the traits contributing majorly to the

Table 3 Pooled range, mean, and genetic variability parameters of agronomic traits in little millet germplasm evaluated in two rainy seasons (2021 and 2022) at ICRISAT, Patancheru, India

S. No	Mean	Range		h^2_b	GCV (%)	PCV (%)	Genetic advance (%)	GA as % mean	LSD (5%)	CV (%)
		Min	Max							
Days to 50% flowering	70.59	41	107	0.97	12.00	12.18	17.19	24.36	2.16	1.89
Days to maturity	97.63	67	134	0.97	8.94	9.10	17.66	18.09	2.66	1.68
Plant height (cm)	168.73	108.11	200.75	0.95	10.14	10.42	34.27	20.31	11.55	4.23
Basal tillers per plant	6	5	11	0.55	13.17	17.75	1.31	20.14	1.40	13.37
Flag leaf blade length (mm)	270.53	230.42	299.72	0.70	5.45	6.53	25.33	9.36	31.99	7.30
Flag leaf blade width (mm)	11.14	9.31	12.38	0.67	5.45	6.67	1.02	9.16	1.55	8.61
Flag leaf sheath length (mm)	103.00	84.01	129.49	0.81	7.14	7.93	13.64	13.24	1.41	0.85
Peduncle length (mm)	127.32	111.05	154.53	0.43	5.50	8.38	9.46	7.43	21.09	10.23
Panicle exertion (mm)	24.34	3.57	63.35	0.67	42.13	51.42	17.31	71.11	14.40	36.51
Inflorescence length (mm)	308.56	246.40	349.39	0.75	5.67	6.56	31.12	10.09	28.17	5.64
Inflorescence width (mm)	248.94	187.09	286.91	0.67	6.94	8.46	29.23	11.74	28.43	7.05
Inflorescence primary branch length (mm)	167.31	108.50	224.53	0.78	12.27	13.87	37.42	22.37	24.20	8.93
Nodes per plant on main stalk	8	6	9	0.78	7.12	8.06	1.04	12.97	0.82	6.32
Leaves per plant on main stalk	9	7	11	0.76	6.31	7.25	1.03	11.30	0.84	5.71
Culm thickness (mm)	7.95	4.58	9.43	0.86	11.22	12.13	1.70	21.38	1.01	7.83
100 Seed weight (g)	0.19	0.14	0.25	0.88	10.31	10.99	0.04	19.94	0.02	7.24
Grain yield (Kg/ha)	2216	1521	2768	0.48	8.45	12.20	267.41	12.07	336.10	9.36
Stover fresh weight (Kg/ha)	17,764	3863	37,521	0.92	33.04	34.40	2786.85	65.37	722.96	10.47
Stover dry weight (Kg/ha)	6701	1800	17,836	0.91	32.10	33.66	1014.49	63.08	320.98	12.32
Harvest Index	0.27	0.09	0.50	0.89	21.73	23.07	0.11	42.00	0.04	9.42

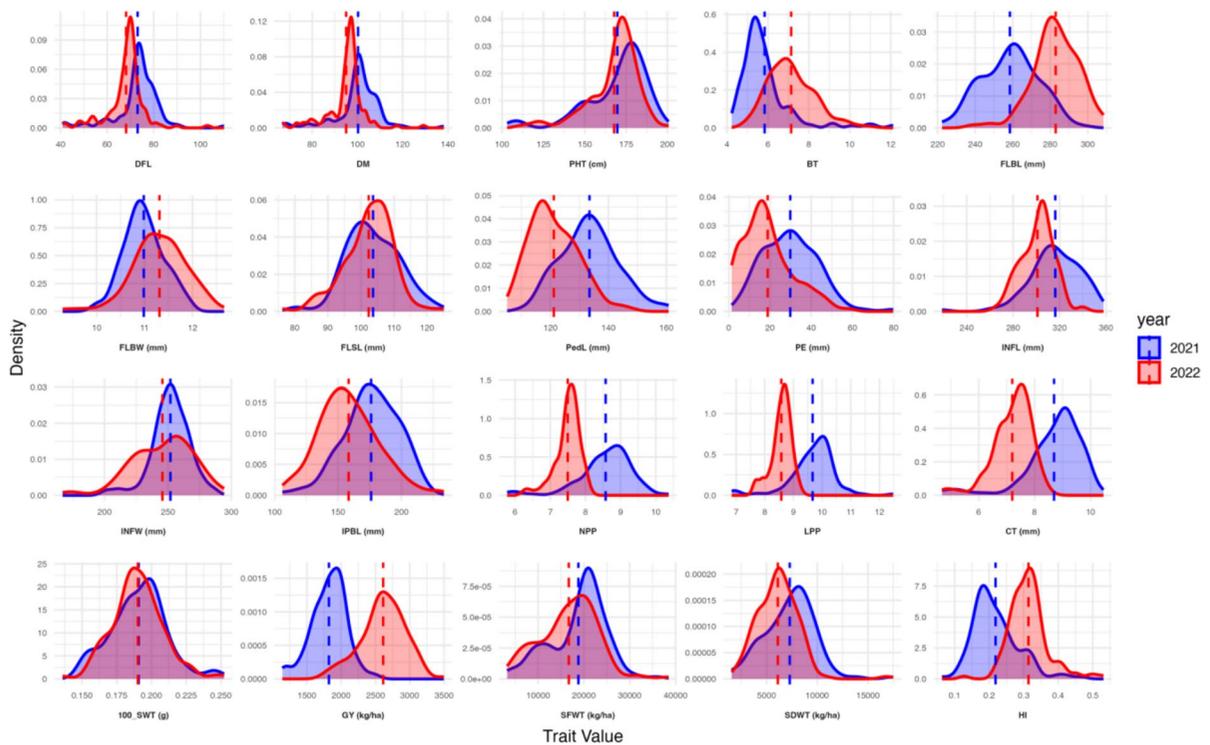


Fig. 1 Kernel Density plots of grain yield and other quantitative traits of little millet germplasm evaluated during the rainy 2021 and 2022 at ICRISSAT Hyderabad. Note: DFL—days to 50% flowering, DM—days to maturity, PHT—plant height (cm), BT—basal tillers per plant, FLBL—flag leaf blade length (mm), FLBW—flag leaf blade width (mm), FLSL—flag leaf sheath length (mm), PedL—peduncle length (mm), PE—panicle exertion (mm), INFL—inflorescence length (mm),

INFW—inflorescence width (mm), IPBL—inflorescence primary branch length (mm), NPP—nodes per plant on main stalk, LPP—leaves per plant on main stalk, CT—culm thickness (mm), 100_SWT—100 seed weight (g), GY—grain yield (kg/ha), SDWT—stover dry weight (kg/ha), SFWT—stover fresh weight (kg/ha), HI—harvest Index. The red and blue vertical lines indicate the mean values of the respective trait during rainy 2021 and 2022

variance explained by PC1. Similarly, inflorescence length, inflorescence width, flag leaf sheath length, flag leaf blade length and inflorescence primary branch length contributed significantly to the variability explained by PC2. From the biplot (Fig. 3), the vector length of the trait indicates its contribution to the total diversity of germplasm. The longer the length of the trait vectors, the greater the contribution to total diversity in the germplasm. Furthermore, the angle between the trait vectors is a measure of correlation. The acute angle between grain yield and days to maturity, days to 50% flowering, stover fresh weight, stover dry weight, 100 seed weight, and nodes per plant on main stalk and leaves per plant on main stalk indicates positive correlations among them. The obtuse angle between the vectors of grain yield and the traits of the harvest index and basal tillers per

plant is a measure of the negative correlation between them.

Cluster analysis

The Euclidean distance matrix calculated based on 20 quantitative traits of 130 little millet accessions, including checks, was used for clustering based on Ward's method, resulting in two major clusters with 91 genotypes in cluster 1 and 39 genotypes in cluster 2 (Fig. 4). Compared to cluster 2, which has lower mean values of 10,266 kg/ha for stover fresh weight and 4,177 kg/ha for stover dry weight, cluster 1 exhibits significantly higher means of 20,977 kg/ha for stover fresh weight and 7,7835 kg/ha for stover dry weight. Similarly, the mean grain yield (kg/ha) of

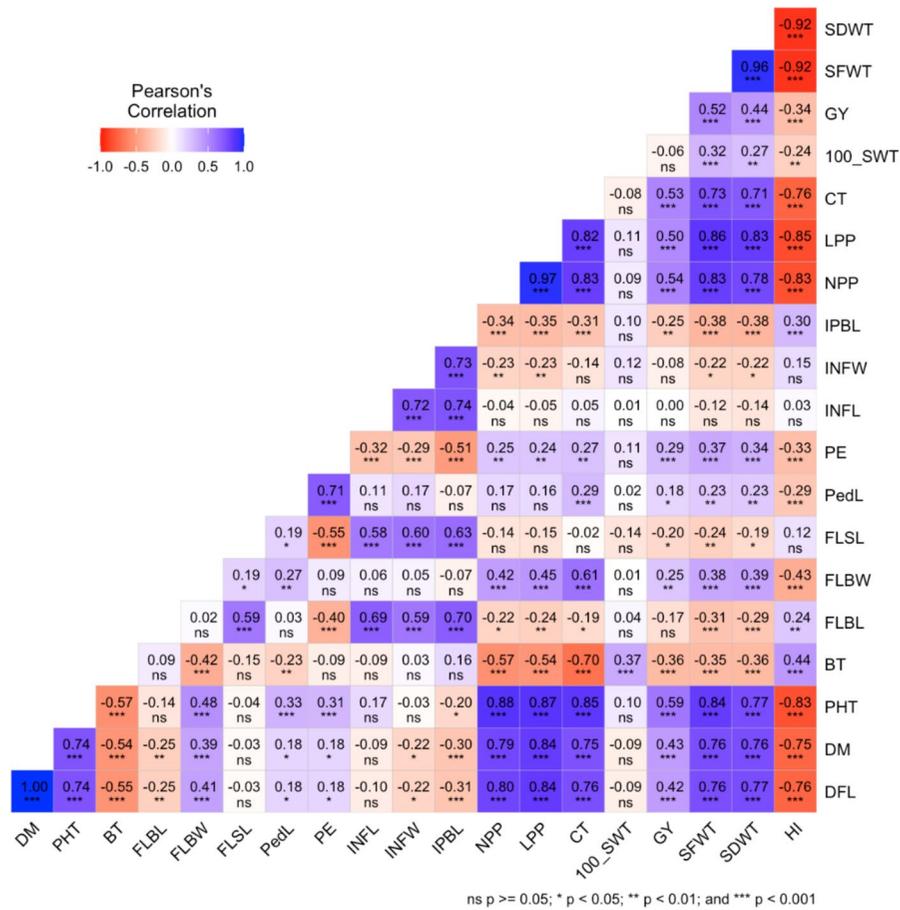


Fig. 2 Correlations between grain yield and various other agro-morphological characteristics of little millet germplasm evaluated at ICRISAT, Hyderabad, during rainy 2021 and 2022. Note: DFL—days to 50% flowering, DM—days to maturity, PHT—plant height (cm), BT—basal tillers per plant, FLBL—flag leaf blade length (mm), FLBW—flag leaf blade width (mm), FLSL—flag leaf sheath length (mm), PedL—

peduncle length (mm), PE—panicle exertion (mm), INFL—inflorescence length (mm), INFW—inflorescence width (mm), IPBL—inflorescence primary branch length (mm), NPP—nodes per plant on main stalk, LPP—leaves per plant on main stalk, CT—culm thickness (mm), 100_SWT—100 seed weight (g), GY—grain yield (kg/ha), SDWT—stover dry weight (kg/ha), SFWT—stover fresh weight (kg/ha), HI—harvest Index

Cluster 1 (2303 kg/ha) was higher than that of Cluster 2 (2014 kg/ha).

Trait-specific accessions

For grain yield, the top 20 accessions were identified based on pooled means, of which 10 are statistically superior to Phule Eka-dashi (grain yield of 2210 kg/ha) (Table 5). Among the top 20 accessions, IPmr 723, IPmr 1042 and IPmr 990 with a pooled mean grain yield of 2674, 2635 and 2603 kg/ha are identified as the top yielding accession which are

statistically superior to the check in pooled and also in individual seasons. The pooled grain yields of the top 10 accessions ranged from 2546 to 2768 kg/ha. These high-grain-yielding accessions matured 95–105 days after sowing. Based on the pooled BLUPs of stover dry weight, 87 accessions based on pooled data, 79 accessions in 2021, and 88 accessions in 2022 were statistically better performers compared to the check GV2. Similarly, in the case of stover fresh weight, most accessions (95 accessions) were statistically superior to BL 6 (11,234 kg/ha) in the pooled, as well as in the 2021 (99 accessions) and 2022 (91 accessions). For fodder yield, the top 20 accessions were

Table 4 Eigenvalue, variance (%) and cumulative variance (%) of major principal components

Principal component	PC1	PC2	PC3	PC4
Eigen value	9.02	3.69	1.69	1.54
Variance %	45.11	18.48	8.45	7.71
Cumulative variance %	45.11	63.59	72.04	79.75
Individual Trait contributions (%) towards PCs				
Traits	PC1	PC2	PC3	PC4
Days to 50% flowering	8.48	0.40	2.93	0.52
Days to maturity	8.38	0.39	2.94	0.54
Plant height (cm)	8.88	2.08	0.47	0.01
Basal tillers per plant	3.87	2.09	12.16	7.16
Flag leaf blade length (mm)	1.52	14.73	0.62	0.07
Flag leaf blade width (mm)	2.81	2.76	0.24	2.47
Flag leaf sheath length (mm)	0.55	17.61	1.59	0.48
Peduncle length (mm)	1.02	0.81	13.00	36.50
Panicle exertion (mm)	1.95	5.00	15.86	21.06
Inflorescence length (mm)	0.29	19.89	0.91	0.01
Inflorescence width (mm)	1.00	16.29	3.98	0.33
Inflorescence primary branch length (mm)	2.51	15.63	0.77	1.40
Nodes per plant on main stalk	9.43	0.36	0.17	1.12
Leaves per plant on main stalk	9.76	0.31	0.11	1.86
Culm thickness (mm)	8.65	1.28	1.23	1.09
100 seed weight (g)	0.05	0.00	34.99	15.51
Stover fresh weight (kg/ha)	9.34	0.00	3.38	3.23
Stover dry weight (kg/ha)	8.89	0.00	2.41	3.13
Harvest Index	8.92	0.35	2.22	1.73
Grain yield (kg/ha)	3.72	0.03	0.00	1.76

identified based on the pooled BLUPs of stover dry weight. Stover dry weight of these identified top 20 accessions ranges from 8,648 to 17,386 kg/ha and matured in 95 to 134 days after sowing (Table 6). Five accessions, namely IPmr 880, IPmr 871, IPmr 875, IPmr 896 and IPmr 907, were identified as dual-purpose producing significantly high grain and stover yields.

Discussion

Crops such as small millets, which have received little breeding push, are, in general, low-yielding compared to those that have received global systematic breeding support from the public and private sectors; hence, these crops need basic information on the potential of the germplasm that could be used for further improving their productivity. Unveiling genetic diversity through the evaluation of germplasm resources and

the identification of trait-specific sources is essential for exploring untapped genetic potential. This could also enhance the utility of the existing germplasm resources for their improvement. The current study on little millet revealed the existence of high variability for yield and biomass contributing traits, which will be an asset to its breeding program. The high heritability of most traits indicates a greater potential for successful selection for the improvement of various traits. Among the various traits, higher heritability was observed for important traits such as days to 50% flowering, days to maturity, plant height, inflorescence length and width, 100 seed weight, and stover fresh and dry weight in the pooled data of two seasons. Traits with high heritability and high genetic advance are mostly governed by additive gene action, for which selection is much more effective. Further, significant improvement is also possible for the traits having medium heritability and high genetic advance (% mean). Non-additive gene action was

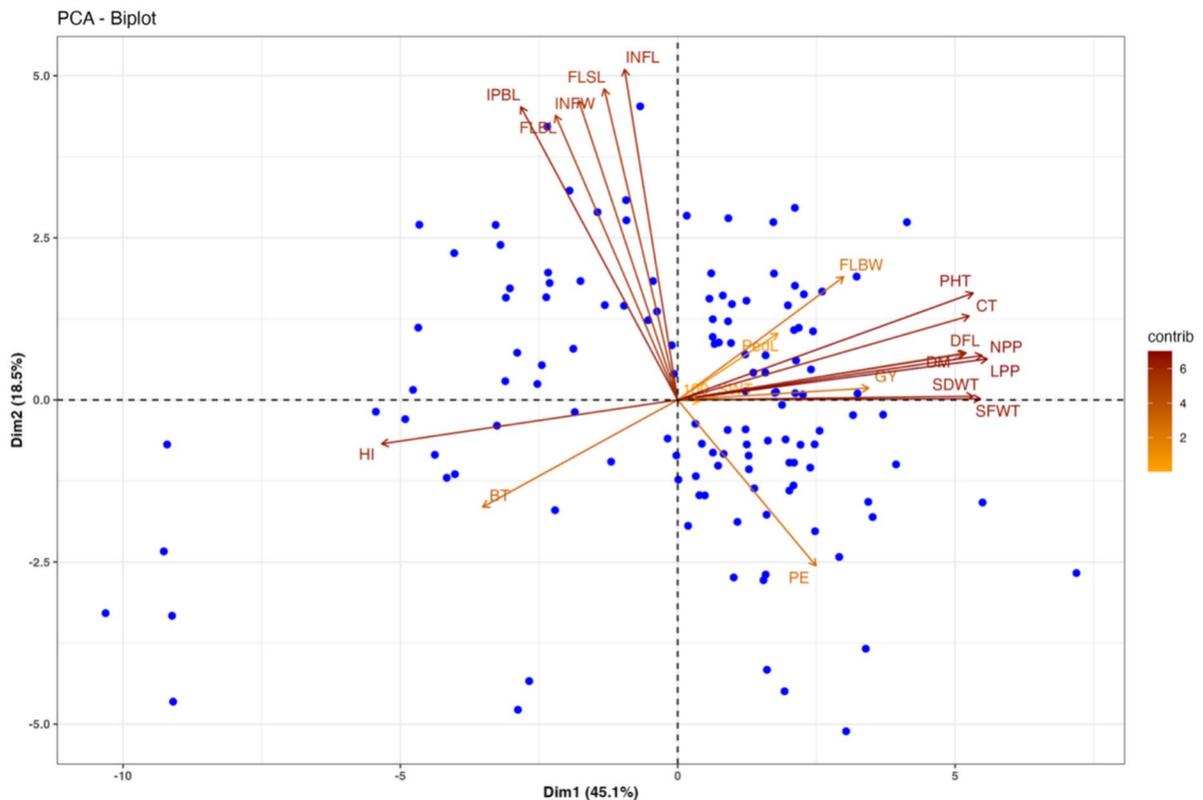


Fig. 3 Bi-plot of principal component analysis of various agro-morphological traits of little millet germplasm. Note: DFL—days to 50% flowering, DM—days to maturity, PHT—plant height (cm), BT—basal tillers per plant, FLBL—flag leaf blade length (mm), FLBW—flag leaf blade width (mm), FLSL—flag leaf sheath length (mm), PedL—peduncle length (mm), PE—panicle exertion (mm), INFL—inflorescence

length (mm), INFW—inflorescence width (mm), IPBL—inflorescence primary branch length (mm), NPP—nodes per plant on main stalk, LPP—leaves per plant on main stalk, CT—culm thickness (mm), 100_SWT—100 seed weight (g), GY—grain yield (kg/ha), SDWT—stover dry weight (kg/ha), SFWT—stover fresh weight (kg/ha), HI—harvest Index

predominant for traits with low heritability and low genetic advance as % mean, for which recombination breeding would be the most suitable method of trait improvement. Grain yield showed medium heritability and medium genetic advance as % mean, while some investigations reported high heritability and high genetic advance (Behera et al. 2024). This proves that improvement in grain yield is possible through hybridization followed by selection. Traits such as stover fresh and dry weights showed high heritability and high genetic advance as % the mean. Therefore, the fodder yield can be improved through direct selection from the identified trait-specific sources. Medium heritability and genetic advance for grain yield highlight the value of indirect selection for genotypes based on positively associated traits. Traits

such as days to 50% flowering, plant height, and days to maturity were positively associated with grain yield in this study and negatively associated with basal tillers per plant. A similar correlation was observed when both races of little millet were assessed in our previous study (Vetriventhan et al. 2021).

The association is caused by both direct and indirect effects; consideration of direct effects alone can enhance the scope of success of trait improvement (Kumar et al. 2024). In the case of days to maturity, peduncle length, leaves per plant on main stalk, culm thickness and stover dry weight, the positive association was due to larger positive indirect effects of various traits dominating their direct negative association with grain yield (kg/ha). A positive association due to the dominance of direct

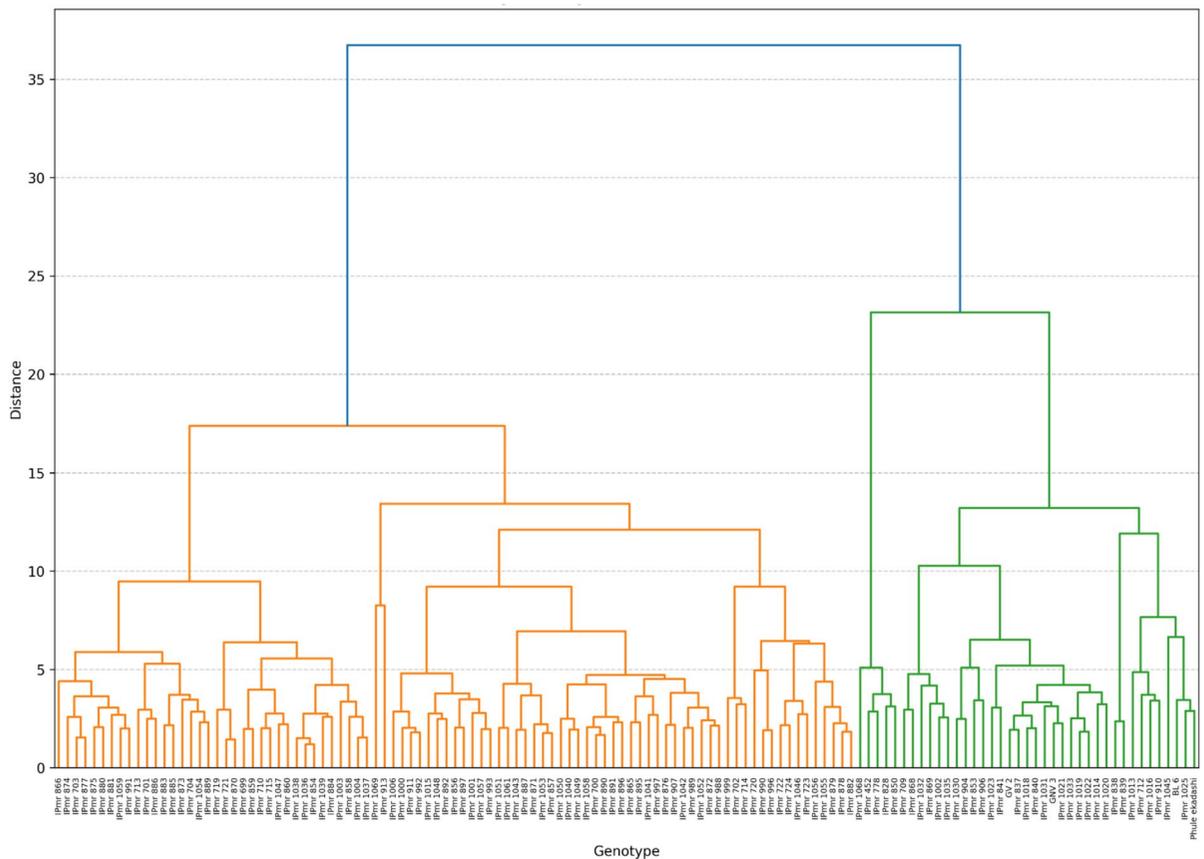


Fig. 4 Hierarchical clustering of 130 little millet germplasm accessions based on Ward's method and Euclidean distance

effects on grain yield was observed in the case of days to 50% flowering, plant height, panicle exertion, nodes per plant on main stalk, and the stover fresh weight. Correlation between grain yield and harvest index was negligible in 2021, negative in 2022, and in the pooled data of both seasons. Some investigations reported a significant positive relationship (Patel et al. 2023; Behera et al. 2024), while our previous study indicated a negligible relationship when both races were studied together (Vetriventhan et al. 2021). The negative correlation in the pooled data of both seasons in the current study was due to the greater indirect negative effects of stover fresh weight on the positive direct effects of harvest index. In a previous study (Patel et al. 2023), the dominance of the direct positive effects of the harvest index over the negative indirect effects of fodder yield resulted in a positive correlation in little millet. The dominance of the indirect effects of stover fresh weight on grain yield

is a measure of the greater fodder potential of *robusta* over the grain yield potential, which agrees with a previous study (Vetriventhan et al. 2021). Moreover, as the positive direct effects are much higher in the case of days to 50% flowering, panicle exertion, and stover fresh weight, these are the best indices for indirect selection for the improvement of grain yield.

The first four principal components together accounted for 79.75% of the total variation, and the traits, namely days to 50% flowering, days to maturity, plant height, nodes per plant on main stalk, leaves per plant on main stalk, culm thickness, stover fresh weight, and stover dry weight and harvest index were the traits contributed significantly to total variance. Cluster analysis divided the 130 genotypes into two different clusters, and all four cultivars used as checks grouped under a single cluster, indicating a similarity in performance based on overall traits. Hybridization between the most diverse accessions,

Table 5 Little millet germplasm accessions identified for high grain yield and their agronomic characteristics

Accessions	Grain yield (kg/ha)			Days to 50% flowering			Days to maturity			Plant height (cm)		
	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022
IPmr 714	2768*	2438*	3039	71	72	70	98	99	97	175	175	175
IPmr 723	2674*	2176*	3138*	72	75	68	98	101	95	180	182	178
IPmr 1050	2643*	2504*	2705	71	74	67	99	102	95	169	170	168
IPmr 1042	2635*	2071*	3180*	77	80	74	105	109	100	178	176	180
IPmr 896	2615*	2221*	2975	70	72	68	97	98	95	176	178	174
IPmr 990	2603*	2056*	3134*	75	74	77	102	101	104	176	169	183
IPmr 891	2572*	1912	3223*	72	75	68	98	101	96	178	184	172
IPmr 989	2564*	2056*	3057	76	81	71	103	108	97	180	178	181
IPmr 875	2556*	1640	3497*	75	81	70	103	110	97	172	168	176
IPmr 880	2546*	2129*	2933	74	77	70	101	106	97	181	183	179
IPmr 1040	2524	2254*	2759	72	74	70	101	104	98	176	180	172
IPmr 999	2518	2007*	3009	77	80	74	104	108	100	174	174	173
IPmr 871	2518	2322*	2661	70	72	68	96	98	95	184	192	176
IPmr 1003	2487	2064*	2899	70	74	67	98	102	95	165	163	167
IPmr 722	2482	1997*	2939	72	75	69	99	102	96	167	174	161
IPmr 1049	2480	2062*	2897	68	70	66	95	96	94	176	179	174
IPmr 1032	2464	2188*	2713	76	75	76	102	101	104	168	164	172
IPmr 1053	2456	1930	2981	78	80	76	104	106	103	173	174	173
IPmr 996	2456	2026*	2873	73	74	71	99	100	98	172	172	171
IPmr 907	2452	2060*	2801	74	77	70	101	105	98	188	189	185
Controls												
BL 6	1928	1585	2290	52	50	54	80	80	81	152	149	157
GNV 3	2185	1851	2525	69	72	67	97	99	94	155	150	160
GV 2	1905	1664	2179	69	72	67	96	98	94	149	151	147
Phule Ekadashi	2210	1628	2810	51	52	51	77	78	76	146	136	158
Trial mean	2216	1821	2612	71	73	68	98	170	95	169	170	168
Minimum	1521	1143	1747	41	41	41	67	103	67	108	103	111
Maximum	2768	2504	3497	107	110	103	134	199	129	201	199	201
LSD (5%)	336	350	321	2	2	2	3	3	2	12	10	13
CV (%)	9.36	11.90	7.59	1.89	1.76	2.01	1.68	1.77	1.58	4.23	3.61	4.79

* Indicates statistical superiority over the check (Phule Ekadashi) at 5% level of significance

resulting in heterosis followed by selection, can be beneficial for improving grain yield and other traits governed by non-additive gene action. Thus, clustering can provide a basis for selecting the most diverse genotype.

The identification of trait-specific sources, resulting in a major focus on these genetic resources, can improve breeding programs. The top 10 trait-specific sources identified for grain yield based on the pooled data are superior to Phule Ekadashi. Accession IPmr 723, IPmr 1042, and IPmr 990 were among the top 10 performing accessions in pooled and in both

individual seasons. Most of the high-yielding accessions identified were of medium duration, with a maturity duration of 95 to 105 days. There is a need to attempt to transfer high-yielding potential from identified trait-specific sources into the genetic background of short-duration accessions, as variability among the germplasm screened was large for days to maturity, ranging from 67 to 134 days.

This study also identified the top 20 accessions for stover dry weight yield. As days to maturity were highly positively correlated with stover fresh weight and dry weight, most of the trait-specific accessions

Table 6 Trait-specific accessions of little millet germplasm identified for stover fresh weight (Kg/ha) and dry weight (kg/ha)

Accessions	Stover dry weight (Kg/ha)			Stover fresh weight (Kg/ha)			Plant height (cm)			Days to maturity			Grain Yield (kg/ha)		
	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022
IPmr 913	17,386*	17,482*	16,836*	37,521*	35,913*	38,490*	165	168	162	134	138	129	1701	1191	2254
IPmr 876	11,322*	13,792*	8627*	27,203*	31,390*	22,537*	178	177	179	104	109	99	2259	1797	2711
IPmr 873	10,324*	11,969*	8516*	24,513*	27,353*	21,317*	179	181	175	100	101	99	1988	1482	2520
IPmr 1056	10,266*	9690*	10,690*	29,236*	27,444*	30,808*	201	199	201	111	115	107	2111	1404	2851
IPmr 702	10,028*	11,267*	8652*	25,732*	26,531*	24,806*	177	176	179	102	105	100	2322	1823	2822
IPmr 1054	9775*	10,243*	9187*	25,596*	26,271*	24,710*	189	195	182	111	114	108	2284	1826	2745
IPmr 703	9712*	10,742*	8567*	22,952*	25,478*	20,284*	178	186	171	100	101	98	2234	1792	2684
IPmr 882	9614*	10,702*	8332*	23,376*	25,596*	20,817*	190	191	188	106	110	102	2315	1615	3033
IPmr 1069	9541*	11,357*	7554*	31,312*	30,030*	32,204*	191	192	188	119	120	117	1957	1702	2213
IPmr 907	9435*	10,167*	8563*	26,543*	27,401*	25,325*	188	189	185	101	105	98	2452	2060	2801
IPmr 874	9286*	9677*	8811*	22,597*	22,071*	23,047*	176	181	172	95	98	93	2114	1400	2871
IPmr 878	9282*	10,043*	8355*	23,090*	25,449*	20,397*	190	191	189	103	106	100	2174	1868	2489
IPmr 1051	9193*	10,108*	8102*	25,048*	26,632*	23,033*	184	192	176	106	109	104	2417	1739	3087
IPmr 877	9133*	9684*	8524*	24,209*	23,972*	24,458*	182	185	178	101	106	96	2325	1647	3027
IPmr 871	9061*	9521*	8433*	23,019*	25,947*	19,668*	184	192	176	96	98	95	2518	2322	2661
IPmr 701	9055*	8688*	9291*	23,178*	21,166*	25,114*	190	187	192	102	107	98	2190	1816	2561
IPmr 700	9000*	8647*	9162*	22,238*	19,022*	25,277*	182	178	184	99	101	98	2413	1713	3111
IPmr 875	8918*	8780*	9012*	24,071*	22,405*	25,730*	172	168	176	103	110	97	2556	1640	3497
IPmr 896	8706*	9401*	7934*	24,396*	25,375*	23,150*	176	178	174	97	98	95	2615	2221	2975
IPmr 880	8648*	10,123*	7037*	22,747*	23,791*	21,503*	181	183	179	101	106	97	2546	2129	2933
Controls															
BL 6	3925	3742	4227	11,234	10,543	12,145	152	149	157	80	80	81	1928	1585	2290
GNV 3	4510	5432	3715	10,772	13,181	8578	155	150	160	97	99	94	2185	1851	2525
GV 2	4684	5372	4135	9598	12,104	7309	149	151	147	96	98	94	1905	1664	2179
Phule Ekaadashi	4010	3752	4432	10,940	10,486	11,773	146	136	158	77	78	76	2210	1628	2810
Trial mean	6701	7284	6113	17,764	18,800	16,709	169	170	168	98	170	95	2216	1821	2612
Minimum	1800	1565	2023	3863	3245	3988	108	103	111	67	103	67	1521	1143	1747
Maximum	17,386	17,482	16,836	37,521	35,913	38,490	201	199	201	134	199	129	2768	2504	3497
LSD (5%)	1337	1489	1158	3012	3609	2223	201	199	201	3	3	2	336	350	321
CV (%)	12.32	12.64	11.72	10.47	11.88	8.23	11.55	9.9	12.99	1.68	1.77	1.58	9.36	11.90	7.59

* Indicates statistical superiority over the check (GV 2 for Stover dry weight (kg/ha) and BL 6 for Stover fresh weight (kg/ha) at 5% level of significance

for high biomass were 95 to 134 days to maturity. Accessions, namely IPmr 913, IPmr 876, IPmr 873, IPmr 1056 and IPmr 702 are among the top five. In addition to the fodder potential, consideration of the fodder quality can improve its utility to a much greater extent. Our attempts to study the fodder quality of 20 little millet accessions (unpublished) indicated a mean IVMOD of 47.33% (range 46.08–48.82%), which is comparable to finger millet (Backiyalakshmi et al. 2021) and wheat (mean ~48%) (Blümmel et al. 2019) while higher than the reported value in rice (mean 42%, range 38.2 to 45.6%) (Subudhi et al. 2020). Similarly, crude protein content in little millet ranged from 5.44 to 8.33% with a mean of 6.78% (unpublished), which is similar to finger millet (mean 7.23%, range 6.47 to 8.15%) (Backiyalakshmi et al. 2021) and higher than that of rice (mean 5.56%, range 4.23 to 7.88%) (Subudhi et al. 2020). This indicates the greater potential of little millet as a fodder crop.

Among small millet crops, the stover dry yield of finger millet ranged from 2890–10779 kg/ha, and accessions with multiple fodder quality aspects have been reported (Backiyalakshmi et al. 2021). Similarly, the stover dry yield in the case of kodo millet ranged from 1156–8777 kg/ha (Vettriventhan and Upadhyaya 2019) and the dry biomass in the proso millet germplasm ranged from 2909 to 9775 kg/ha (Calamai et al. 2020). The proso millet cultivar TNAU 151 has a fodder potential of 4130 kg/ha with 72 days to maturing (Nirmalakumari et al. 2011). The mean dry matter yield in sweet sorghum is about 20.18 t/ha, and 18.49 t/ha and 20.62 t/ha in dual-purpose and forage type, respectively (Singh and Chauhan 2017). The average dry straw yield of commercial rice cultivars is around 9.7 t/ha (Matías et al. 2019) and in the case of pearl millet under rainfed conditions, it ranges from 11.8 to 16.4 t/ha (Dhedhi et al. 2016). The stover dry weight of little millet germplasm, evaluated in this study, ranged from 1.8 to 17.8 t/ha. Further, the top accessions identified for stover dry weight ranged from 8.6 t/ha to 17.8 t/ha, highlighting the importance of genetic variability and the potential for selecting and breeding high-yielding cultivars for improved grain and fodder production.

Conclusion

This study's findings open up significant opportunities for little millet breeding programs focused on forage or dual-purpose cultivation. The potential for developing cultivars with high grain and fodder yield having early maturity is particularly promising, as it could address the growing demand for grain and fodder requirements while maintaining efficient crop cycles. There are five accessions identified as dual purpose (IPmr 871, IPmr 875, IPmr 880, IPmr 896 and IPmr 907), which could be explored through multilocation testing and further use in the breeding program. This dual-purpose approach could enhance the economic viability of little millet cultivation, making it more attractive to farmers and potentially increasing its adoption in diverse agricultural systems. Furthermore, the exploration of little millet as a bioenergy crop represents an exciting new frontier in its utilization. Drawing parallels with switch grass (*Panicum virgatum* L.), which has already established itself as a valuable bioenergy source, little millet's potential in this area could be substantial. This multifaceted utility—encompassing grain yield, fodder production, and bioenergy potential—positions little millet as a highly versatile crop. Such versatility could play a crucial role in promoting crop diversification, enhancing agricultural sustainability, and contributing to food, feed, and energy security in various regions. As research in this area progresses, it may lead to the development of specialized little millet cultivars optimized for specific end-uses, further expanding its agricultural and industrial applications.

Author contributions MV and KS contributed to the design and implementation of the research; MV and DN conducted the experiment; JK and DN analysed the data; JK & MV wrote the first draft of the manuscript. All authors reviewed the manuscript.

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Data availability All the required data are provided in the manuscript and as Supplementary Tables. Researchers can approach the corresponding author for any additional information required.

Declarations

Conflict of interest The authors declare no competing interests.

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