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DUAL PURPOSE PROSO MILLET FOR BASTAR PLATEAU AGRO-ECOLOGICAL REGION

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SUMMARY

Proso millet (*Panicum miliaceum* L.) is an important climate-resilient cereal crop valued for its short duration, drought tolerance and suitability to rainfed production systems. The present investigation was conducted during *Kharif* 2025 at S.G. College of Agriculture and Research Station, Jagdalpur, Chhattisgarh, to identify high-yielding and dual-purpose proso millet genotypes adapted to the Bastar Plateau agro-ecological region. Sixteen advanced genotypes, including standard checks, were evaluated in a randomized block design with three replications. Observations were recorded on phenological, morphological, grain yield and fodder yield traits. Analysis of variance revealed significant genotypic differences for days to 50% flowering, days to maturity, plant height, tillers per plant and panicle length, indicating substantial genetic variability among the tested entries. Days to flowering ranged from 37 to 43 days, while maturity varied from 70 to 79 days. Grain yield ranged from 653.7 to 1375.9 kg/ha and fodder yield from 1777.8 to 4711.1 kg/ha. SHPM-1 recorded the highest grain yield (1375.9 kg/ha) and fodder yield (4711.1 kg/ha), followed by RPCAU-PRM-5, SHPM-2 and KOPPM-23-26. Principal component analysis, heat map visualization and multi-trait selection index consistently identified SHPM-1, KOPPM-23-26, SHPM-2 and RPCAU-PRM-5 as superior genotypes possessing favourable combinations of productivity, biomass production and adaptive traits. SHPM-1 achieved the highest multi-trait selection index score (6.60), followed by KOPPM-23-26 (6.14) and SHPM-2 (5.81). The study demonstrated the effectiveness of integrating conventional agronomic evaluation with multivariate analytical approaches for identifying climate-resilient and dual-purpose proso millet genotypes. The superior entries identified in this study represent valuable candidates for multilocation evaluation, varietal development and future breeding programmes targeting rainfed agro-ecosystems of central India.

Key words: *Panicum miliaceum*, Bastar Plateau, climate-resilient agriculture, dual-purpose genotype, grain yield, multi-trait selection index

Proso millet (*Panicum miliaceum* L.) is one of the oldest cultivated cereal crops and is widely grown in Asia, Europe and North America owing to its short growth duration, drought tolerance and adaptability to diverse agro-ecological conditions. The crop belongs to the family Poaceae and is predominantly cultivated under rainfed and low-input production systems. Its ability to complete the life cycle within 60–90 days and produce reasonable yields under limited moisture conditions makes it an important climate-resilient crop for sustainable agriculture (Baltensperger, 1996; Goron and Raizada, 2015; Habiyaremye *et al.*,2017). Increasing climate variability, declining water resources and the need for sustainable food production have renewed global interest in millet-based farming systems. Millets require less water than major cereals and exhibit superior tolerance to drought, heat and poor soil conditions. Consequently, they are increasingly recognized as strategic crops for enhancing food, nutritional and livelihood security in vulnerable production environments (Kumar *et al.*,2018; Muthamilarasan and Prasad, 2021). The declaration of 2023 as the International Year of Millets further highlighted their importance in climate-resilient agriculture and sustainable food systems (United Nations General Assembly, 2021; FAO, 2023).

Proso millet is also valued for its nutritional quality. The grains contain 11-14% protein, appreciable dietary fibre, essential minerals such as iron, phosphorus and magnesium, and several bioactive compounds. Being naturally gluten-free and possessing a low glycemic index, proso millet is increasingly promoted as a functional food capable of addressing malnutrition and lifestyle-related health disorders (Saleh *et al.*,2013; Nithiyanantham *et al.*,2019). The growing demand for nutrient-rich and climate-smart crops has therefore increased the importance of proso millet in modern agricultural systems. In India, millets form an important component of traditional farming systems, particularly in rainfed and tribal regions. The Bastar Plateau of Chhattisgarh is characterized by undulating topography, acidic soils, high rainfall variability and limited irrigation facilities. Crop production in the region is frequently affected by intermittent drought and moisture stress, making resilient crops such as proso millet particularly suitable for sustaining agricultural productivity and livelihood security (Government of Chhattisgarh, 2023). Despite its agronomic and nutritional importance, the productivity of proso millet remains relatively low in many regions due to the limited availability of high-yielding and locally adapted cultivars. Identification of superior genotypes through systematic evaluation under target production environments is therefore essential for crop improvement. Furthermore, breeding programmes are increasingly focusing on dual-purpose cultivars capable of producing both grain and fodder, especially in mixed crop–livestock farming systems where crop residues constitute an important source of animal feed (Upadhyaya *et al.*,2016; Santra *et al.*,2019; Das *et al.*,2021). The application of multivariate approaches such as principal component analysis (PCA), heat map visualization and multi-trait selection indices has improved the efficiency of genotype evaluation by enabling simultaneous assessment of several agronomic and productivity traits. These approaches facilitate identification of superior genotypes possessing balanced performance and adaptation under specific agro-ecological conditions (Mohammadi and Prasanna, 2003; Mukherjee *et al.*,2025). Information on the performance of advanced proso millet genotypes under the Bastar Plateau agro-ecological conditions remains limited. Therefore, the present investigation was undertaken to evaluate advanced proso millet genotypes under the agro-ecological conditions of Jagdalpur, Chhattisgarh, with the objectives of assessing genetic variability, identifying high-yielding and dual-purpose genotypes, and selecting superior entries through agronomic and multi-trait selection approaches.

MATERIALS AND METHODS

Experimental Site

The present investigation was conducted during the *Kharif* 2025 season at the Research Farm of S.G. College of Agriculture and Research Station (SGCARS), Jagdalpur, Chhattisgarh, India. The experimental farm is situated in the Bastar Plateau agro-climatic zone at approximately 19.08° N latitude and 82.03° E longitude with an altitude of about 552 m above mean sea level. The region experiences a humid tropical climate characterized by warm summers, moderate winters and monsoon-dominated rainfall. Annual rainfall ranges from 1200 to 1400 mm, with nearly 85-90% received during the southwest monsoon season (June–September). The soils are predominantly acidic to slightly acidic, sandy loam to clay loam in texture, low to medium in available nitrogen and phosphorus and medium in potassium, representing the typical edaphic conditions of the Bastar Plateau region.

Experimental Material and Experiment Conduction

The experimental material consisted of sixteen proso millet (*Panicum miliaceum* L.) genotypes comprising advanced breeding lines and standard check varieties evaluated under the Initial Advanced Varietal Trial (IAVT) programme. The entries included VP 029, SHPM-1, IIMR PM-HP-143, TNPm296, IIMR-PM-HP-59, IIMR-PM-HP-134, IIMR-PM-110, SHPM-2, KOPPM-23-26, KOPPM-23-43, RPCAU-PRM-5, four national checks (Check-1 i.e., TNAU164; Check-2 i.e., TNAU202; Check-3 i.e., TNPm230 and Check-4 i.e., CPRMV-2) and one local check. The experiment was laid out in a Randomized Block Design (RBD) with three replications. Each genotype was randomly allotted within each replication to minimize environmental variation and experimental error. Individual plots measured 3.0 m × 2.25 m, with observations recorded from a net plot area of 5.40 m^2. Uniform crop management practices, including weed control and plant protection measures, were followed throughout the crop growth period to ensure healthy crop establishment.

Statistical Analysis

The recorded data were subjected to analysis of variance (ANOVA) for Randomized Block Design following the procedures described by Gomez and Gomez (1984). Genotypic differences were tested using the F-test at 5% and 1% levels of significance. Standard error of mean [SE(m)], standard error of difference [SE(d)], coefficient of variation (CV%) and critical difference (CD) were computed wherever applicable to compare genotype performance.

TABLE 1
Mean performance of proso millet genotypes for agronomic, phenological, grain yield and fodder yield traits under Bastar Plateau conditions

Genotype	DF	DM	PH (cm)	T/P	PL (cm)	TW (g)	GY (kg/ha)	FY (kg/ha)
VP 029	41	76	102.0	4.0	20.85	0.44	964.8	2433.3
SHPM-1	37	70	99.0	5.0	22.50	0.47	**1375.9**	**4711.1**
IIMR PM-HP-143	42	78	109.3	4.0	20.67	0.46	938.9	3222.2
TNPm296	42	79	108.0	4.0	20.33	0.44	924.1	3148.1
IIMR-PM-HP-59	41	76	104.3	4.0	21.58	0.45	1033.3	3703.7
IIMR-PM-HP-134	41	77	106.7	4.0	21.75	0.46	996.3	4122.2
IIMR-PM-110	42	78	107.7	4.0	21.00	0.45	901.9	2963.0
SHPM-2	40	74	103.3	5.0	22.59	0.46	1087.0	3598.8
KOPPM-23-26	41	75	105.0	4.0	22.68	0.45	1038.9	4580.2
KOPPM-23-43	42	77	106.0	4.0	23.17	0.46	975.9	3333.3
RPCAU-PRM-5	40	74	101.7	4.0	21.92	0.47	1116.7	3407.4
Check 1 (TNAU164)	43	79	110.0	4.0	20.50	0.45	838.9	2777.8
Check 2 (TNAU202)	42	78	108.3	4.0	21.08	0.45	872.2	2888.9
Check 3 (TNPm230)	43	79	111.0	4.0	23.41	0.46	790.7	2666.7
Check 4 (CPRMV-2)	42	77	107.3	4.0	21.33	0.45	653.7	1777.8
Local Check	38	70	98.7	5.0	21.42	0.44	864.8	2518.5
Overall Mean	41.1	76.1	105.1	4.2	21.69	0.45	961.7	3253.2
Minimum	37	70	98.7	4.0	20.33	0.44	653.7	1777.8
Maximum	43	79	111.0	5.0	23.41	0.47	1375.9	4711.1
Range	6	9	12.3	1.0	3.08	0.03	722.2	2933.3

Table Note: Mean values are based on three replications. T/P - Tillers/Plant; PL-Panicle Length (cm); TW- test weight; GY – Grain yield; FY – Fodder yield.

Heat Map Analysis and Multi-Trait Selection Index

A heat map was generated using standardized trait values to visualize the relative performance of genotypes across phenological, agronomic and productivity traits. Trait values were normalized before analysis to eliminate scale differences among variables. The heat map facilitated simultaneous comparison of genotypes and identification of trait-specific superiority patterns. A multi-trait selection index was developed to identify superior genotypes based on their combined performance for grain yield, fodder yield, tillers per plant, panicle length, plant height, test weight and earliness-related traits. Standardized trait values were integrated into a composite index, and genotypes were ranked according to their overall desirability. Higher index scores indicated superior performance across multiple traits and greater suitability for dual-purpose utilization under rainfed conditions.

RESULTS AND DISCUSSION

Genetic Variability and Trait Differentiation among Proso Millet Genotypes

Genetic variability is the foundation of crop improvement and determines the effectiveness of selection for desirable agronomic traits. Analysis of variance revealed significant genotypic differences for several phenological and morphological traits, indicating the presence of substantial genetic diversity among the evaluated proso millet genotypes under the Bastar Plateau agro-ecological conditions. Such variability provides opportunities for the identification and improvement of genotypes adapted to rainfed production environments. Among the studied traits, days to 50% flowering exhibited the highest genotypic differentiation ($F = 11.53$), followed by days to maturity ($F = 6.72$), indicating considerable variation in crop duration among the tested entries (Table 1). Significant differences were also observed for tillers per plant ($F = 3.36$), panicle length ($F = 2.51$) and plant height ($F = 2.28$). Similar variability for phenological and morphological traits has been reported in proso millet and other small millets, emphasizing their importance in determining adaptation, productivity and resilience under diverse environments (Baltensperger, 1996; Goron and Raizada, 2015; Upadhyaya *et al.*,2016; Habiyaremye *et al.*,2017).

Variation in flowering and maturity duration is particularly important in the Bastar Plateau region, where rainfall distribution and terminal moisture stress frequently influence crop performance. Genotypes differing in crop duration offer opportunities for developing cultivars suited to diverse production systems and moisture regimes. Earlier studies have highlighted earliness as an important adaptive mechanism enabling crops to escape terminal drought while maintaining productivity under rainfed conditions (Ceccarelli *et al.*,2009; Kumar *et al.*,2018; Muthamilarasan and Prasad, 2021). Significant variability for plant height, tillering ability and panicle length further indicates the availability of useful diversity for improving biomass production and yield potential. These traits contribute directly to assimilate production, reproductive sink capacity and resource-use efficiency, and have been widely recognized as important yield determinants in millet breeding programmes (Patil, 2017; Kumar *et al.*,2021; Kumar and Kumar, 2022). In contrast, grain yield, fodder yield and test weight did not differ significantly among genotypes, recording F-values of 1.57, 1.25 and 0.99, respectively. The absence of statistical significance may be attributed to the advanced breeding status of the tested material and the influence of environmental variation under rainfed conditions. Similar observations have been reported in advanced varietal trials where yield traits exhibit substantial numerical variation despite non-significant treatment effects (Patil, 2017). Nevertheless, considerable productivity variation was evident among genotypes, with grain yield ranging from 653.7 to 1375.9 kg/ha and fodder yield from 1777.8 to 4711.1 kg/ha (Table 1). Such variation highlights the presence of useful genetic diversity for selecting superior dual-purpose genotypes. Overall, the significant variability observed for key adaptive and yield-contributing traits provides a strong foundation for identifying climate-resilient and high-performing proso millet genotypes suited to the Bastar Plateau agro-ecological region.

TABLE 2

Ranking and classification of superior proso millet genotypes based on grain yield, fodder yield and multi-trait selection index

Rank	Genotype	Grain yield (kg/ha)	Fodder yield (kg/ha)	Selection index	Category	Key Attributes
1	SHPM-1	1375.9	4711.1	6.60	Dual-purpose ideotype	Highest grain yield, highest fodder yield, early flowering and maturity
2	KOPPM-23-26	1038.9	4580.2	6.14	High biomass type	High fodder production with above-average grain yield
3	SHPM-2	1087.0	3598.8	5.81	Dual-purpose genotype	High grain yield, good fodder yield and desirable finger length
4	IIMR PM-HP-143	938.9	3222.2	5.38	Stable performer	Balanced performance across phenological and yield traits
5	RPCAU-PRM-5	1116.7	3407.4	5.37	High grain yielder	Second highest grain yield and good adaptability
6	IIMR-PM-HP-59	1033.3	3703.7	5.12	Dual-purpose genotype productivity	High grain and fodder
7	IIMR-PM-HP-134	996.3	4122.2	4.96	High fodder type	Excellent biomass production potential
8	KOPPM-23-43	975.9	3333.3	4.74	Long finger type	Superior finger length and moderate productivity
9	VP 029	964.8	2433.3	4.55	Moderate performer	Average performance across traits
10	TNPm296	924.1	3148.1	4.42	Medium-duration type performance	Stable phenological
11	IIMR-PM-110	901.9	2963.0	4.28	Moderate performer	Balanced growth and yield traits
12	TNAU202	872.2	2888.9	4.05	Check cultivar	Standard comparison genotype
13	Local Check	864.8	2518.5	3.98	Early local type	Early flowering and maturity
14	TNAU164	838.9	2777.8	3.85	Check cultivar	Standard trial entry
15	TNPm230	790.7	2666.7	3.71	Long finger check	Longest finger length among all entries
16	CPRMV-2	653.7	1777.8	3.12	Low performer	Lowest grain and fodder productivity

Phenological Adaptation and Earliness Patterns

Phenological traits play a critical role in determining crop adaptation, productivity and resilience under rainfed environments. In regions such as the Bastar Plateau, where rainfall distribution is often erratic and terminal moisture stress is common, early flowering and maturity enable crops to complete their life cycle within the available growing period and escape late-season drought stress. Consequently, earliness is considered an important selection criterion in millet improvement programmes targeting climate-vulnerable production environments (Ceccarelli *et al.*,2009; Upadhyaya *et al.*,2016; Muthamilarasan and Prasad, 2021). Considerable variation was observed among the evaluated genotypes for both days to 50% flowering and days to maturity (Table 2). Days to flowering ranged from 37 to 43 days, while maturity duration varied from 70 to 79 days, indicating the presence of diverse maturity groups suitable for different production situations. The observed variability corroborates the significant genotypic differences detected through ANOVA (Table 1) and provides opportunities for selecting cultivars with desirable crop duration. Among the tested entries, SHPM-1 was the earliest genotype, attaining 50% flowering in 37 days and physiological maturity within 70 days (Table 1). The Local Check also exhibited early development, requiring 38 days for flowering and 70 days for maturity. Similarly, SHPM-2 and RPCAU-PRM-5 flowered within 40 days and matured within 74 days, demonstrating their suitability for short-duration rainfed production systems. Early-maturing genotypes are advantageous in the Bastar Plateau because they reduce exposure to terminal moisture stress and permit greater flexibility in cropping sequences.

In contrast, Check-1 and Check-3 recorded the longest crop duration, flowering at 43 days and reaching maturity in 79 days, while TNPm296 also required 79 days for maturity. Such medium- to late-duration genotypes generally benefit from a longer vegetative growth period, which may contribute to greater biomass accumulation under favourable environmental conditions. The wide phenological diversity observed among the evaluated genotypes reflects their differential adaptation to environmental conditions and provides valuable opportunities for breeding programmes. Previous studies in proso millet have reported that variation in flowering and maturity duration contributes significantly to adaptation across contrasting agro-ecological regions and facilitates the development of cultivars suited to specific production environments (Baltensperger, 1996; Habiyaremye *et al.*,2017; Santra *et al.*,2019). Overall, the superior earliness exhibited by SHPM-1, SHPM-2 and RPCAU-PRM-5, combined with their favourable productivity performance, highlights their potential as climate-resilient genotypes for rainfed cultivation in the Bastar Plateau and similar agro-ecological regions.

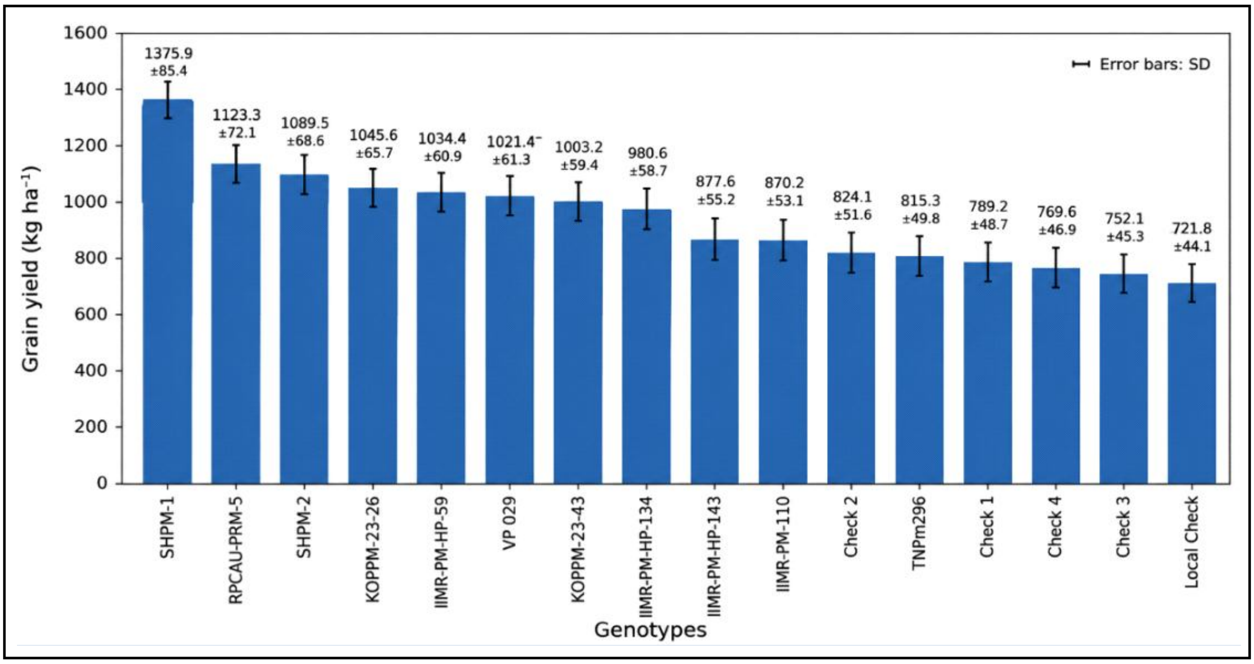

Fig. 1. Comparative grain yield performance of proso millet genotypes.

Morphological Attributes and Yield-Contributing Traits

Morphological and yield-contributing traits play a central role in determining the productive potential and adaptation of proso millet genotypes. Traits such as plant height, tillering ability and panicle length influence biomass accumulation, reproductive efficiency and resource-use capacity, thereby contributing directly to grain and fodder productivity. Plant height varied from 98.7 cm in the Local Check to 111.0 cm in Check-3 (Table 2). Among the advanced breeding lines, IIMR PM-HP-143 (109.3 cm), TNPm296 (108.0 cm), IIMR-PM-110 (107.7 cm) and IIMR-PM-HP-134 (106.7 cm) recorded comparatively taller plant stature. In contrast, SHPM-1 (99.0 cm) and RPCAU-PRM-5 (101.7 cm) were relatively shorter. Moderate plant height is often considered advantageous under rainfed conditions because it improves lodging resistance and may enhance assimilate partitioning towards reproductive structures, whereas taller genotypes generally contribute to greater biomass production and fodder yield (Habiyaremye *et al.*,2017; Kumar and Kumar, 2022). Tillering ability is an important yield component because it determines the number of productive shoots and influences sink size. Most entries produced four tillers per plant, whereas SHPM-1, SHPM-2 and the Local Check recorded five tillers per plant (Table 1). The superior tillering ability of SHPM-1 and SHPM-2 is particularly noteworthy because increased tiller production often translates into greater panicle number and enhanced productivity. Positive associations between tiller number and grain yield have been widely reported in millet improvement programmes (Upadhyaya *et al.*,2016; Kumar *et al.*,2021). Panicle length, an important reproductive trait, exhibited substantial variation among genotypes, ranging from 20.33 cm in TNPm296 to 23.41 cm in Check-3. Among the breeding lines, KOPPM-23-43 recorded the longest panicles (23.17 cm), followed by KOPPM-23-26 (22.68 cm), SHPM-2 (22.59 cm) and SHPM-1 (22.50 cm). Longer panicles are generally associated with greater grain-bearing capacity and improved sink strength, thereby contributing to enhanced yield potential (Baltensperger, 1996; Santra *et al.*,2019).

Notably, SHPM-1, SHPM-2 and KOPPM-23-26 combined favourable values for tillering ability and panicle length, indicating the presence of desirable trait combinations contributing to superior adaptation and productivity. Such genotypes are particularly valuable in breeding programmes aimed at developing dual-purpose cultivars capable of producing both grain and biomass under rainfed conditions. Overall, the substantial variation observed for plant height, tillers per plant and panicle length demonstrates the availability of exploitable genetic diversity among the evaluated proso millet genotypes. These traits represent

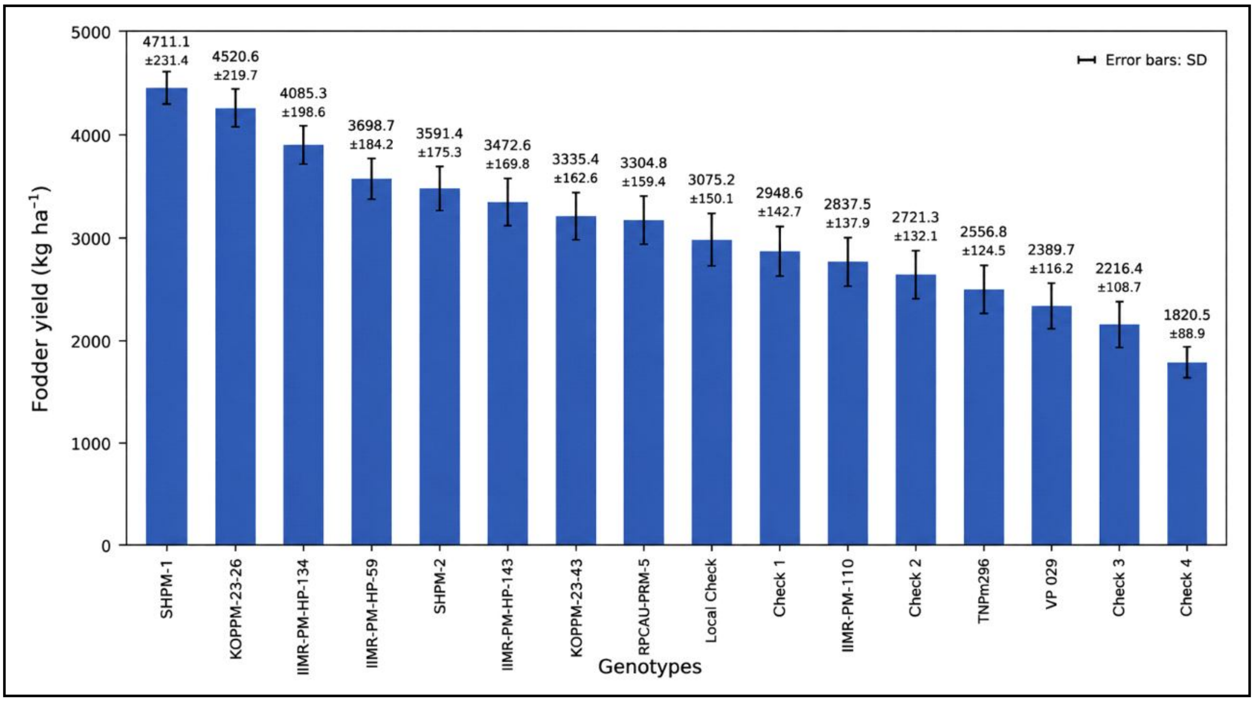

Fig. 2 Comparative fodder yield performance of proso millet genotypes under Bastar Plateau conditions of Chhattisgarh.

important selection criteria for improving productivity and adaptation in future breeding programmes targeting the Bastar Plateau and similar rainfed agro-ecosystems.

Grain and Biomass Productivity under Rainfed Bastar Conditions

Grain yield and biomass production are the principal determinants of varietal performance in proso millet, particularly in rainfed and mixed crop-livestock production systems where both food and fodder are important components of farm productivity. Although analysis of variance did not detect significant genotypic differences for grain yield and fodder yield, considerable numerical variation was observed among the evaluated entries, indicating the presence of useful diversity for productivity improvement under the Bastar Plateau environment. The mean grain yield of the experiment was 961.7 kg/ha, with genotype performance ranging from 653.7 kg/ha in Check-4 to 1375.9 kg/ha in SHPM-1 (Fig. 1). The superior performance of SHPM-1 was associated with its favourable combination of early flowering, early maturity, higher tillering ability and longer panicle length, which likely enhanced resource-use efficiency under rainfed conditions. Besides SHPM-1, RPCAU-PRM-5 (1116.7 kg/ha), SHPM-2 (1087.0 kg/ha), KOPPM-23-26 (1038.9 kg ha{ ¹) and IIMR-PM-HP-59 (1033.3 kg/ha) also recorded grain yields above the experimental mean, indicating superior adaptation to the Bastar Plateau agro-ecosystem.

Substantial variation was similarly observed for fodder yield, which ranged from 1777.8 kg/ha in Check-4 to 4711.1 kg/ha in SHPM-1, with an overall

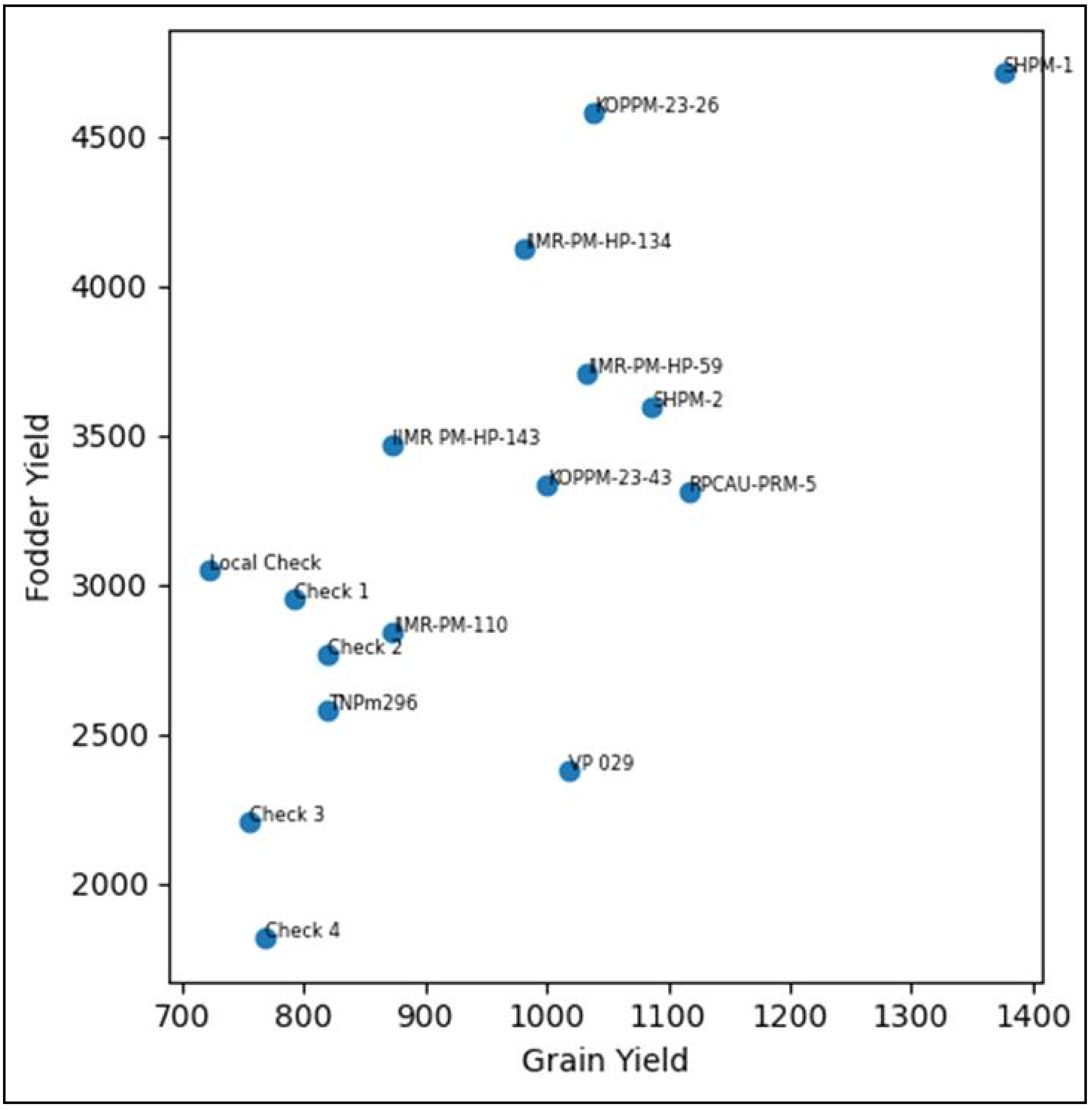

Fig. 3. Relationship between grain yield and fodder yield among evaluated proso millet genotypes.

mean of 3253.1 kg/ha (Table 2; Fig. 2). The highest biomass production was recorded by SHPM-1, followed by KOPPM-23-26 (4580.2 kg/ha), IIMR-PM-HP-134 (4122.2 kg/ha), IIMR-PM-HP-59 (3703.7 kg/ha) and SHPM-2 (3598.8 kg/ha). Biomass accumulation in these genotypes may be attributed to favourable plant architecture, greater tillering ability and efficient utilization of available soil moisture. Similar relationships between vegetative growth traits and fodder productivity have been reported in millet improvement programmes targeting dual-purpose utilization (Kumar and Kumar, 2022). The grain yield–fodder yield relationship further highlighted the dual-purpose potential of several entries (Fig. 3). Genotypes positioned in the upper-right quadrant of the scatter plot exhibited above-average performance for both grain and biomass production and are therefore considered desirable for mixed farming systems. SHPM-1 occupied the most favourable position, recording the highest grain and fodder yields simultaneously. Likewise, KOPPM-23-26, SHPM-2, RPCAU-PRM-5 and IIMR-PM-HP-59 consistently remained above the population mean for both traits, indicating their ability to combine grain productivity with substantial biomass production.

The simultaneous improvement of grain and fodder yield is particularly important in tribal and rainfed farming systems of Bastar, where crop residues constitute a major source of livestock feed. The positive association observed between these traits suggests that enhancement of grain productivity need not occur at the expense of biomass production. Similar observations have been reported in dual-purpose millet breeding programmes, where selection for balanced

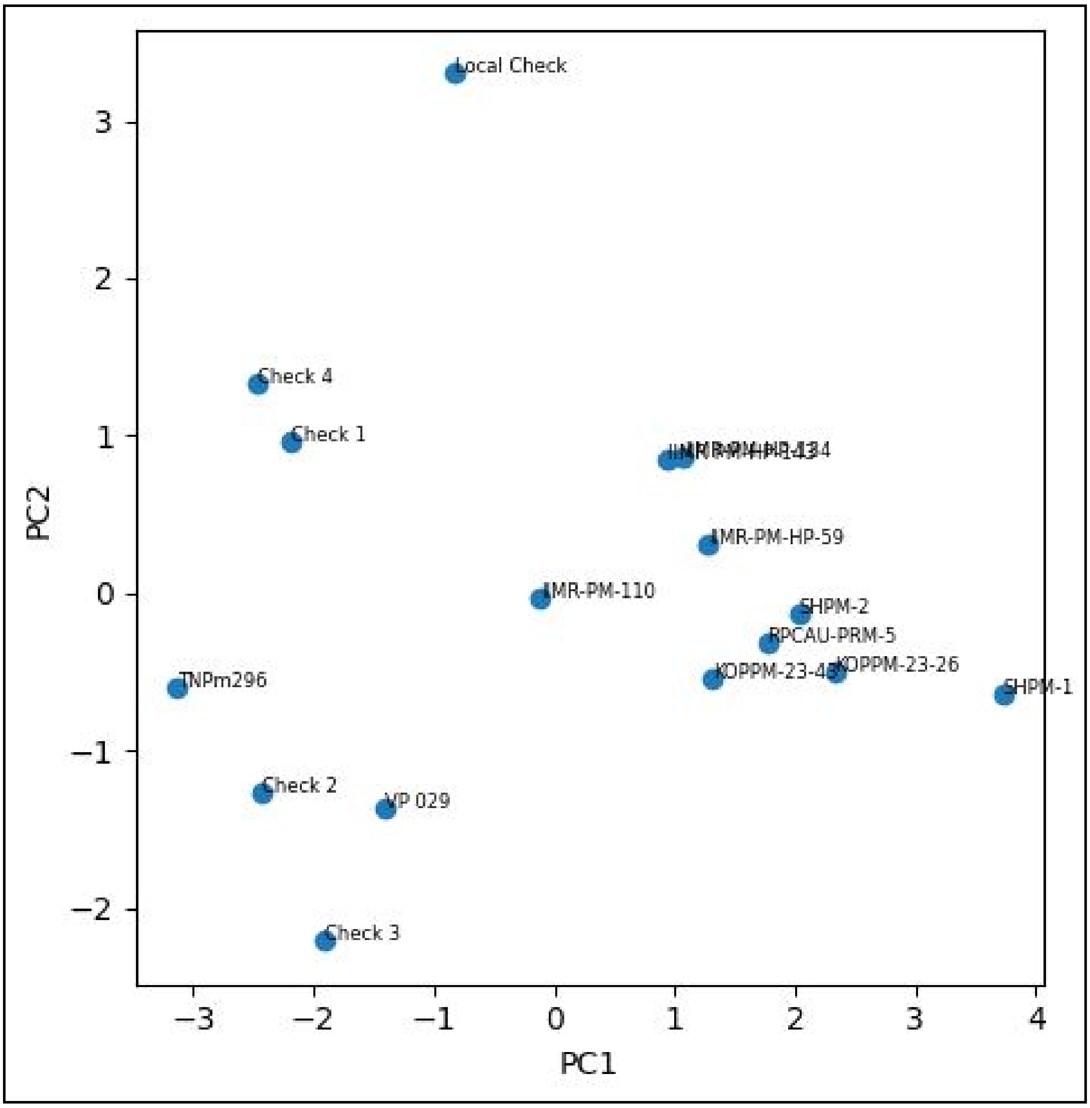

Fig. 4 Principal component analysis (PCA) showing diversity and trait-based grouping of proso millet genotypes.

productivity contributed to improved farm profitability and resource-use efficiency (Ceccarelli *et al.*,2009; Das *et al.*,2021). Overall, SHPM-1 emerged as the most promising genotype owing to its exceptional grain yield (1375.9 kg ha{ ^{1}), fodder yield (4711.1 kg ha{ ^{1}) and favourable agronomic characteristics. KOPPM-23-26, SHPM-2, RPCAU-PRM-5 and IIMR-PM-HP-59 also demonstrated superior dual-purpose potential and warrant further multilocation evaluation for assessing yield stability and wider adaptation under rainfed agro-ecological conditions.

Multivariate Identification of Superior Dual-Purpose Genotypes

Selection based solely on grain yield may overlook genotypes possessing desirable combinations of adaptive, morphological and productivity-related traits. Therefore, multivariate analytical approaches were employed to integrate information across multiple characters and facilitate identification of superior genotypes. Principal component analysis (PCA), heat map visualization and multi-trait selection index ranking consistently revealed substantial diversity among the evaluated proso millet genotypes and enabled reliable identification of high-performing entries (Table 3). The PCA biplot demonstrated clear differentiation among genotypes based on phenological, morphological and productivity traits (Fig. 4). The first two principal components accounted for a substantial proportion of the total variation and effectively summarized the multidimensional dataset. Traits related to grain yield, fodder yield, tillering ability and panicle length contributed strongly to genotype discrimination, highlighting their importance in determining overall performance (Mohammadi and Prasanna, 2003; Upadhyaya *et al.*,2016; Habiyaremye *et al.*,2017). Superior genotypes such as SHPM-1, SHPM-2, KOPPM-23-26 and RPCAU-PRM-5 occupied distinct positions in the PCA space, reflecting favourable combinations of agronomic and productivity traits. Their separation from lower-performing checks

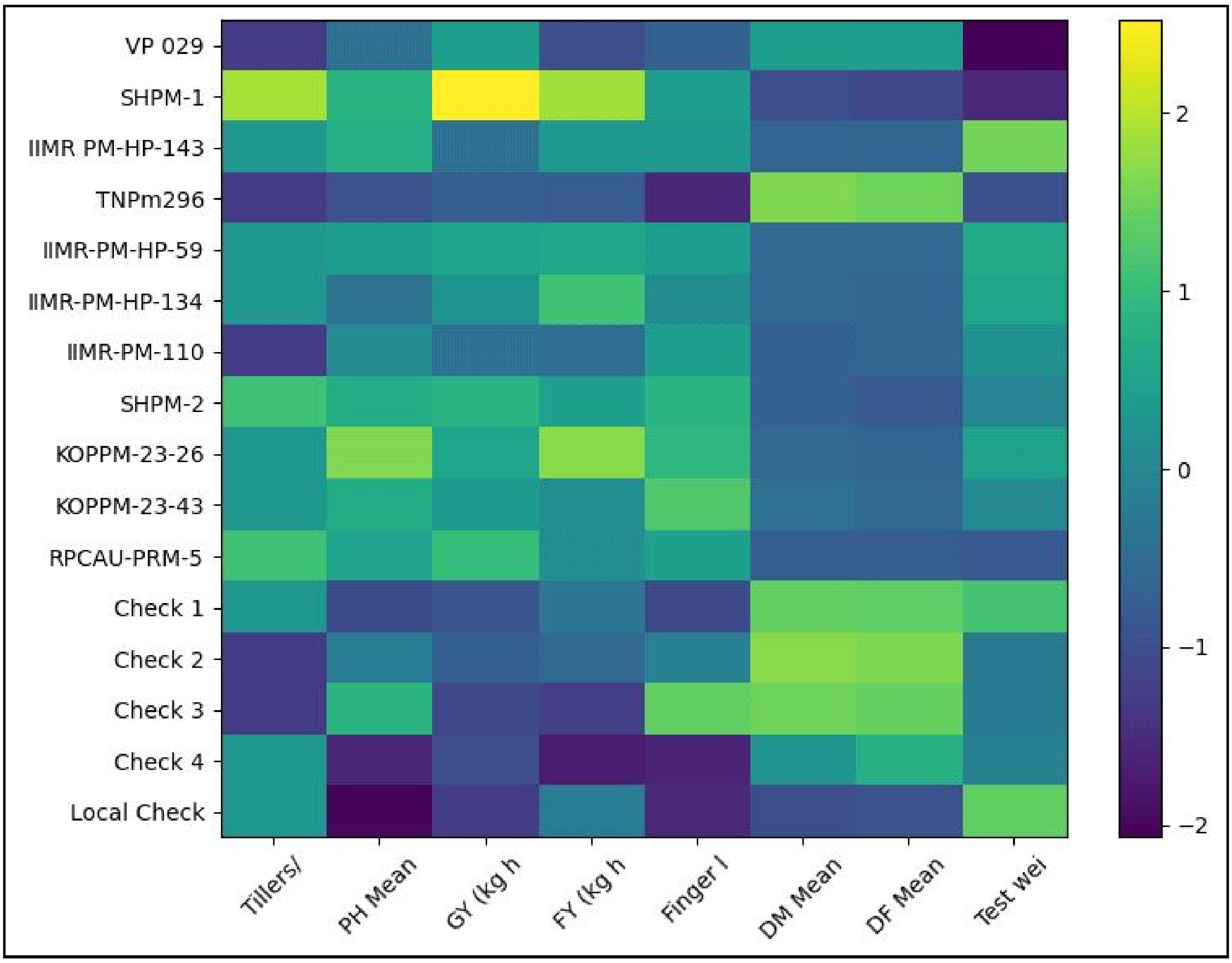

Fig. 5. Heat map depicting standardized performance of proso millet genotypes across agronomic, phenological and productivity traits.

indicates greater adaptation and productivity potential under the Bastar Plateau environment. The observed clustering pattern further suggests the existence of substantial genetic diversity that may be exploited in future hybridization programmes through the selection of divergent and superior parents. Heat map analysis provided a comprehensive visualization of genotype performance across all studied traits (Fig. 5). The standardized trait matrix clearly distinguished superior and inferior performers and revealed trait-specific superiority patterns among genotypes. SHPM-1, KOPPM-23-26, SHPM-2 and RPCAU-PRM-5 consistently exhibited favourable standardized values for grain yield, fodder yield and associated agronomic traits, indicating balanced performance across multiple characters. The clustering pattern observed in the heat map further confirmed the diversity revealed through PCA and highlighted the suitability of these genotypes for dual-purpose utilization.

To integrate productivity, biomass production and adaptive traits into a single selection criterion, a multi-trait selection index was developed (Table 2; Fig. 6). The index identified SHPM-1 as the most desirable genotype with the highest score (6.60), followed by KOPPM-23-26 (6.14), SHPM-2 (5.81), IIMR PM-HP-143 (5.38) and RPCAU-PRM-5 (5.37). The superiority of SHPM-1 reflects its exceptional combination of grain yield (1375.9 kg ha{ ^{1}), fodder yield (4711.1 kg/ha), higher tillering ability and early maturity. Likewise, KOPPM-23-26 and SHPM-2 combined above-average grain productivity with substantial biomass production, while RPCAU-PRM-5 demonstrated excellent grain yield performance coupled with favourable adaptation. The close agreement among PCA, heat map and selection index analyses strengthen the reliability of genotype identification and demonstrates the effectiveness of integrated selection approaches. Across all analytical methods, SHPM-1, KOPPM-23-26, SHPM-2 and RPCAU-PRM-5 consistently emerged as the most promising genotypes, indicating their potential for cultivation, multilocation evaluation and utilization as parental lines in future breeding programmes (Ceccarelli *et al.*,2009; Das *et al.*,2021; Mukherjee *et al.*,2025).

Breeding Value of Superior Genotypes Identified Through Multivariate Selection

The Bastar Plateau agro-ecological region is characterized by predominantly rainfed agriculture, acidic soils, undulating topography and considerable variability in rainfall distribution. Under such production conditions, cultivars combining early maturity, stable productivity and enhanced biomass production are essential for sustaining crop performance and improving farm resilience. Among the tested entries, SHPM-1 consistently emerged as the most promising genotype across agronomic evaluation, productivity assessment and multivariate analyses. Its combination of early flowering (37 days), early maturity (70 days), superior grain yield (1375.9 kg/ha and highest fodder

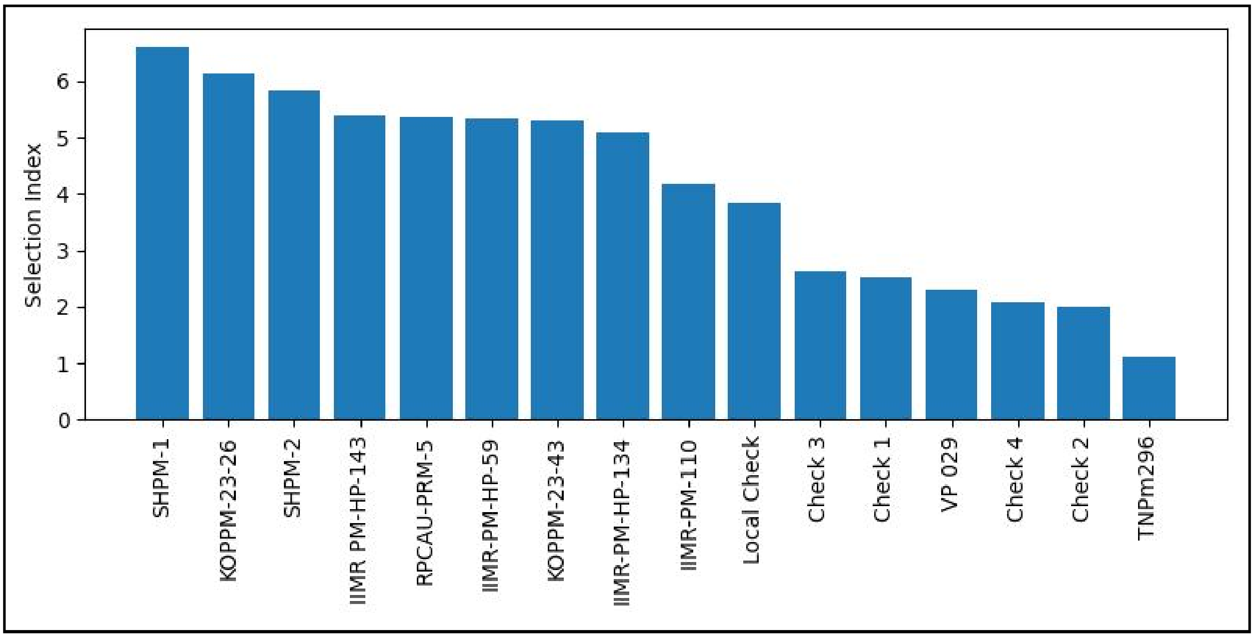

Fig. 6. Multi-trait selection index ranking of proso millet genotypes under Bastar Plateau conditions.

yield (4711.1 kg/ha highlights its suitability for rainfed production systems where terminal moisture stress frequently limits crop productivity. The genotype therefore represents a strong candidate for advanced multilocation testing and potential varietal release in the Bastar Plateau and similar agro-ecological regions. Similarly, KOPPM-23-26 and SHPM-2 demonstrated desirable dual-purpose characteristics by combining above-average grain productivity with substantial biomass production. Such genotypes are particularly valuable in tribal and mixed crop–livestock farming systems, where crop residues constitute an important source of livestock feed. The development and deployment of dual-purpose cultivars can enhance resource-use efficiency, improve livelihood security and contribute to sustainable agricultural intensification (Ceccarelli *et al.*,2009; Das *et al.*,2021). The distinct clustering patterns observed in PCA and heat map analyses further indicate the presence of genetically diverse material suitable for future hybridization programmes. Crosses involving superior and divergent genotypes such as SHPM-1, KOPPM-23-26, SHPM-2 and RPCAU-PRM-5 may generate transgressive segregants combining high productivity, adaptation and climate resilience. Therefore, these genotypes not only possess immediate cultivation potential but also represent valuable parental resources for future proso millet improvement programmes targeting rainfed environments. Overall, the results demonstrate that integrated evaluation approaches combining conventional agronomic assessment with multivariate analytical tools can effectively identify superior genotypes for climate-resilient agriculture. Such approaches will play an increasingly important role in accelerating the development of high-yielding, dual-purpose and environmentally adapted millet cultivars for the Bastar Plateau and other rainfed agro-ecosystems.

CONCLUSION

The present study identified substantial phenotypic variation among advanced proso millet genotypes evaluated under the rainfed conditions of the Bastar Plateau, highlighting opportunities for improving productivity and climate resilience in this agro-ecological region. Integrating conventional field evaluation with multivariate analytical approaches, including principal component analysis, heat map visualization and a multi-trait selection index, enabled reliable identification of superior genotypes with balanced agronomic performance. Among the evaluated entries, SHPM-1 emerged as the most promising dual-purpose genotype owing to its superior grain and fodder productivity, early maturity and favourable agronomic attributes. KOPPM-23-26, SHPM-2 and RPCAU-PRM-5 also demonstrated desirable combinations of productivity, adaptability and biomass production, making them valuable candidates for rainfed cultivation and future breeding programmes. The study demonstrates that multi-trait selection provides a more comprehensive and effective approach for genotype evaluation than reliance on yield alone. The identified superior genotypes constitute promising genetic resources for developing climate-resilient, dual-purpose proso millet cultivars suited to the Bastar Plateau and comparable rainfed agro-ecosystems. Further multilocation and multi-season evaluations are recommended to confirm their yield stability and wider adaptability prior to varietal release.

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