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Assessment of forage yield performance in single crosses and three-way cross hybrids in forage pearl millet (*Pennisetum glaucum* L.)

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Abstract
Pearl millet (*Pennisetum glaucum* L.) is a dual-purpose crop valued for both grain and fodder, particularly in arid and semi-arid regions where livestock-based farming systems are predominant. Ensuring a steady supply of quality forage is critical to sustaining animal productivity, and hybrid breeding plays a central role in achieving this goal. The present study was undertaken to evaluate the forage yield potential of 45 single crosses (F_1) and 40 three-way cross hybrids (TWCHs) developed from elite parental lines at ICAR-Indian Institute of Millets Research, Hyderabad. The experiments were conducted across three seasons (Kharif 2024, Rabi 2024-25, and Summer 2025) in a randomized block design with replications. Seven key traits were assessed in two cuts, namely plant height, days to 50% flowering, number of leaves per plant, leaf-stem ratio, number of tillers per plant, green fodder yield, and dry fodder yield. Analysis of variance revealed highly significant differences among genotypes for all traits, confirming the presence of wide genetic variability and the potential for selection. Among the single crosses, hybrids such as SC6, SC4, SC25, and SC42 exhibited outstanding green forage yield (16.9-36.8 kg/plot) and better dry fodder yield (7.9-18 kg/plot). Similarly, three-way crosses like TWCH6, TWCH18, TWCH33, TWCH36, and TWCH21 recorded the highest biomass production, with total green fodder yield ranging between 21-37 kg/plot and dry fodder yield exceeding 15 kg/plot. These TWCHs also demonstrated strong regrowth ability and better leafiness, indicating superior adaptability to multi-cut systems. This study provides a strong basis for identifying promising hybrid combinations for future breeding programs aimed at improving forage yield, quality, and sustainability in pearl millet.

Keywords: Pearl millet, forage yield, single crosses, three-way cross hybrids, genetic variability, heterosis; hybrid vigour, regrowth potential, multi-cut system, livestock fodder security, sustainability

Introduction

Pearl millet, also known as Bajra, sajja or kambam, is a traditional dry-land grain grown mostly in desert and semi-arid climates. Additionally, to being grown for grain, pearl millet is highly appreciated because of its stover, which serves as a substantial fodder source, particularly in dry locations where it can account for 40-50% of animal dry matter consumption during lean months. Its dual-purpose nature assures food and fodder security in these tough environmental conditions (Ramesh *et al*., 2006) [6].

Pearl millet (*Pennisetum glaucum* L.) is an annual diploid crop, with 14 chromosomes. It is believed to have originated in Africa and belongs to the *Poaceae* family, specifically the *Paniceidae* subfamily. Pearl millet is a highly cross-pollinated crop with protogynous blooming and a windborne pollination mechanism, meeting one of the biological prerequisites for hybrid formation (Pal *et al*., 1996) [5].

In India, pearl millet occupies a central position in forage-based cropping systems. It is extensively cultivated during the kharif season across states such as Rajasthan, Gujarat, Uttar Pradesh, Haryana, and Maharashtra, both as a grain and fodder crop. Its fast regrowth capacity after cutting allows multiple harvests, ensuring a continuous supply of green fodder during lean periods. The crop also contributes significantly to the livestock-based farming systems that sustain rural livelihoods in the country. (Sanjana Reddy *et al*., 2021) [7]

Currently, India is the world's largest producer of milk and is anticipated to generate 400 million tons forage (fodder) by 2050 (Sharma, 2021) [8]. Floods (heavy rains), lack of rainfall (desert environment), pest and disease outbreaks, and low soil fertility all have an impact on the life of farm animals and small-scale farmers in marginal regions. Due to a lack of forage and nutrition, such conditions significantly reduce milking animal productivity in the county. As an instance, India currently faces a net shortfall of 590 million tons of green forage and 468 million tons of dry fodder, and it would require approximately 1013 million tons of green fodder and 631 million tons of dry fodder by 2050 (NITI Aayog, 2018) [4].

Pearl millet is often considered a preferred choice for farmers because of its high forage production capacity, broad adaptability, and quick regrowth after cutting. This makes it suitable for repeated harvests, ensuring a consistent supply of quality green fodder. (Arya *et al*., 2013) [1].

Prior research on fodder quality characteristics in pearl millet breeding material, has shown a great deal of variation. Additionally, substantial variability was noted for forage traits. The Total dry fodder yields of three-way top-cross hybrids was marginally higher than that of OPVs and top-cross hybrids, while forage quality traits were generally similar to OPVs and slightly superior to top-cross hybrids (Gupta *et al*., 2022) [3]. Overall, the best-performing three-way top-cross hybrids out yielded OPVs and top-cross hybrids in both forage yield and quality.

Its potential to provide high yields of nutritionally rich fodder under marginal conditions makes it a focus of ongoing breeding and research programs aimed at improving livestock feeding systems worldwide. With these advantages in mind, this investigation aimed to evaluate the new type of three-way hybrid (TWH) in pearl millet was developed by using promising single crosses and best performing Inbred lines. The present study aimed at assessing the forage yield potential of the three-way cross hybrids in comparison to single crosses to identify the better three-way cross hybrids and single crosse combinations.

Materials and Methods

Characteristics of the study site

The experimental site of present study, The Indian Institute of Millets Research (IIMR), located in Hyderabad, Telangana, is a premier national institute under the Indian Council of Agricultural Research (ICAR). As per Union Budget-2023, ICAR-IIMR was designated as a Centre of Excellence (COE) for the Shree Anna program, with the mission to advance India as a global hub for millet-centric research, knowledge-sharing, and innovation. The institute's Centre of Excellence status supports dissemination of millet-focused research and technologies aiming to elevate India's globl footprint in millet cultivation. It serves as the nodal centre for research and development on millets, including pearl millet, sorghum, finger millet, and small millets.

The experimental site is situated at an altitude of 556 m above msl (mean sea level), positioned at 17º19'31.5" N latitude and 78º23'10.9" E longitude, within the Southern Zone of Telangana State. The field was fairly uniform in terms of topography and soil fertility, with a sandy soil type. Irrigation was provided through an open well located adjacent to the site, supported by an efficient drainage system to maintain proper field conditions.

Experimental Material

The field experiment was conducted at the ICAR-Indian Institute of Millet Research, Rajendranagar, Hyderabad during Kharif (2024), *Rabi* (2024-2025), Summer 2025. The experimental plant material consisting of total of 45 F_1s (Developed earlier by ICAR-IIMR) derived from 10 best parental lines (IIMR AVS lines).The experimental material for the present study includes 45 F_1s (obtained from best Parental lines, IIMR AVS50, IIMR AVS71, IIMR AVS73, IIMR AVS73, IIMR AVS98, IIMR AVS94, IIMR AVS95, IIMR AVS18, IIMR AVS11, IIMR AVS41), Five checks (Nutri fast, Nutri feed, TSFB-15-8, Wonder leaf, Raftaar). These 45 Single crosses (F_1) used for evaluated along with the 10 parents, 5 checks during the Kharif (2024) in RBD design. From these 45 F_1s, 20 promising single crosses used for development of Three-way cross hybrids along with 2 best inbred lines.in next seasons, Total 40 three-way cross (TWC) hybrids were generated by using the 20 best-performing F_1 crosses, two different inbred lines in Randomized Block Design (RBD) in two Replications during Rabi, 2024 [2 rows (3 m length) per plot and plot size was 2 x 0.45 m^2]. each entry accommodated in a two-row plot of 3.0 m length, maintaining a row spacing of 45 cm and a plant-to-plant spacing of 15 cm. During Summer 2024-25, those 40 developed three-way crosses were evaluated along with 2 checks (Raftaar, TSFB-15-8) for forage yield performance. From those 40 TWC hybrids and 45 single crosses (F_1), best performing TWC hybrids and F_1s were identified based on their forage yield traits. These 3 experiments were conducted for evaluating 7 yield attributing traits (Plant height, Days to 50% flowering, Number of tillers per plant, Green fodder yield, Dry fodder yield, Leaf stem ratio) of forage pearl millet in 2 cuts (1st cut and 2nd cut).

Field Experiments

The Field experiment was conducted at the ICAR-Indian Institute of Millet Research, Rajendranagar, Hyderabad in three seasons. [Kharif (2024), Rabi (2024-2025), Summer (2025)]. This study was carried out in 3 field experiments.

1. **Experiment I (Kharif 2024):** Identification promising single crosses (F_1) for development of Three-way cross hybrids (TWCH).
2. **Experiment II (Rabi 2024):** Development of Three-way cross hybrids (TWCH).
3. **Experiment III (Summer 2025):** Assessment of Three-way cross hybrids for forage yield traits.

Experiment I (Kharif 2024)

Experiment I conducted during July-October of 2024. Total 45 single crosses (F_1) [cross id: SC1 to SC 45] were evaluated for identification best crosses for development of Three-way ross hybrids. Evaluation was done RBD design with replications. [2 rows (3 m length) per plot] plot size was 2 x 0.45 m^2. each entry accommodated in a two-row plot of 3.0 m length, maintaining a row spacing of 45 cm and a plant-to-plant spacing of 15 cm. 5 checks (Nutri fast, Nutri feed, TSFB-15-8, Wonder leaf, Raftaar) were used for evaluating forage yield traits of single crosses(F_1). These are popular multi-cut, high-biomass-yielding, single-cross pearl millet hybrids. evaluating 7 yield attributing traits [Plant height (cm), Days to 50% flowering (DFF), Number of tillers per plant, Green fodder yield (GFY), Dry fodder yield (DFY), Leaf stem ratio(L/S)] of forage pearl millet in 2 cuts (1st cut and 2nd cut). Based on the mean performance of 45 F_1s compare to 5 checks, Top 20 promising single crosses (F_1) were identified. These 20 F_1s have better yield traits compare to their parents and checks. These 20 single crosses used for development of TWC hybrids in next season.

Experiment II (Rabi 2024)
During Rabi 2024, 40 TWC hybrids were developed by using 20 promising F_1s and two better inbred lines in RBD design. Each cross (Cross Id: TWCH1 to TWCH 40) was generated from single cross (AXB) and different inbred line (C). It consist 3 different individual parents in their genetic make-up. All recommended agronomic practices and plant protection measures were adopted to raise a healthy crop. To prevent contamination from external pollen, the ear heads of parent plants were enclosed in butter paper bags (30 × 10 cm) immediately after they had partially or fully emerged from the boot leaf sheath. The ideal stage for bagging was when nearly one-third of the inflorescence became visible through the flag leaf sheath. The female panicle was considered ready for pollination once the stigmas were fully exposed, appearing as soft, feathery white structures during full bloom. For pollen collection, the male panicles were covered 2-3 days prior to anthesis, ensuring sufficient pollen availability. Cross-pollination was then carried out in the morning hours, preferably between 7`O clock and 10`O clock. Emasculation in bajra is challenging because of the small flower size and the delayed maturity of anthers compared to stigmas. To avoid contamination, nearly four-fifths of the upper portion of the spike is removed, and the remaining part is bagged before the emergence of styles. Pollination is then carried out either by dusting the exposed stigmas with fresh pollen collected from the selected male plant or by gently shaking a pollen-shedding spike over them. 40 Three-way crosses hybrids developed in this season.

Experiment III (Summer 2025)
Experiment III was conducted in summer 2025. Total 40 three-way cross hybrids were evaluated for forage yield performance. 2 commercial checks (Raftaar, TSFB-15-8) were used for evaluation of three-way cross hybrids. Evaluation was done RBD design with replications. [2 rows (3m length) per plot] plot size was 2 x 0.45 m^2. each entry accommodated in a two-row plot of 3.0 m length, maintaining a row spacing of 45 cm and a plant-to-plant spacing of 15 cm. All recommended agronomic practices and plant protection measures were adopted to raise a healthy crop. among all 40 TWC hybrids, Top ten best performing hybrids were identified.

Data Recording
Observations were recorded on five randomly chosen competitive plants from each entry in every replication (2 replications) for different traits. The average of these five plants was considered for statistical analysis. In all 3 experiments, 7 yield attributing traits (Plant height, Days to 50% flowering, Number of tillers per plant, Green fodder yield, Dry fodder yield, Leaf stem ratio) were recorded in 2 cuts (1^{st} cut and 2^{nd} cut). The plant height (PH) was measured (cm) by selecting a fully matured plant and measuring the length from the base of the plant at the soil level to the base of the spike at the time of first cut. Days to 50% flowering (DFF) was recorded as the number of days from the sowing date to the day on which 50% of the plants in a plot reached the anthesis at least half way down the panicle. The total number of productive tillers on a randomly selected plant was counted at the flowering stage. The number of leaves (NL) were counted from top to bottom of randomly selected plant at the time of dough stage. Green fodder yield (GFY) was determined for each sample by harvesting the plants from an area (2m x 0.45m with 2 rows). First cut of fodder (GFY-1) was harvested 75 days after sowing (DAS). Second cut fodder (GFY-2) was harvested 30 days after the first cut. The fresh weight of the harvested material was measured using a digital weighing machine. Green fodder yield was weighed in kilograms per plot (kg/plot), after that it was converted into tonnes/hectare (t/ha). Dry fodder yield was estimated from an area (2 m x 0.45 m with 2 rows) for each entry after the second cut. Green fodder yield in the second cut was dried in sunlight for 15 days and weighed. Dry fodder yield was weighed in kilograms per plot (kg/plot), after that it was converted into tonnes/hectare (t/ha). Leaf stem ratio (LSR) was estimated on fresh weight-basis, five plants were randomly selected from each entry. Leaves were separated from the stems at time of first cut. Average fresh weight of leaves and stems were determined.

Statistical analysis
The experimental data of all three experiments were analysed using the average values (Mean) obtained from randomly selected plants across both replications (R1, R2) in two cuts (First cut and second cut), and these mean values were then subjected to the following statistical analysis:

a) Analysis of variance (ANOVA) for RBD (The design of experiment). The ANOVA was conducted for each quantitative trait to partition the total variability into components due to replication, treatments, and experimental error. The significance of differences among replications and genotypes was assessed using the F-test.
b) Mean and Range values of both single crosses and three-way cross hybrids.

Mean and range
The mean value for each character was estimated using the following formula:

$$\bar{X} = \frac{\sum_{i=1}^{N} X_i}{N}$$

Where,
$\bar{X}$ = Mean of observations,

$$\sum_{i=1}^{N} X_i$$

= Sum of all observation,

N = Number of observations.

Range: Range for each trait was determined by considering the lowest and highest observed values in the dataset.

Range = Maximum value −Minimum value

INDOSTAT software was used for statistical analysis of single cross and three-way cross hybrids.

4. Results and Discussion

The results from both single crosses and TWC hybrids confirm the presence of substantial genetic variability for yield and yield-contributing traits. The observed differences not only establish the genetic diversity within the experimental material but also highlight the opportunity to identify promising hybrids with enhanced forage yield potential.

For single crosses, most of these traits were significant at the 1% level, whereas number of tillers at first cut, regenerated tillers, and new tillers were significant at the 5% level. This confirms the existence of ample genetic diversity, in line with earlier reports highlighting significant variation for forage yield and related traits in pearl millet hybrid parents and single crosses. This results were accordance with earlier studies (Govintharaj *et al*., 2017) [10].

For three-way cross hybrids (Table 2), ANOVA results similarly demonstrated significant genetic differences among the hybrids, parental lines, and checks for most traits. Plant height at both cuts, days to 50% flowering, number of leaves per plant, and leaf-to-stem ratio were significant at the 1% level, reflecting high variability for morphological traits. Fodder yield traits like GFY at both cuts, DFY at both cuts, TGFY, and TDFY were also significant at the 1% level, emphasizing their contribution to yield differentiation among the TWC hybrids. Variability in TWC hybrids are related with earlier studies conducted by (Gupta *et al*., 2018) [9].

Mean performances of single crosses and three-way crosses along with respective checks

The evaluation of forty-five single crosses of pearl mill*et al*.ong with the check variety 'Raftaar' revealed considerable variation across the studied traits (Table 3). Plant height measured at the first cut (PH-1) ranged from 173.0 cm (SC38) to 217.50 cm (SC12), while the mean value was 197.66 cm. For the second cut plant height (PH-2), values varied between 167.41 cm (SC38) and 211.17 cm (SC42) with an average of 187.82 cm.

Days to 50% flowering (DFF) exhibited a wide range, spanning from 47.5 days (SC25) to 62.0 days (SC39), with a grand mean of 55.23 days. Earliness was particularly notable in SC25, whereas SC39 recorded the maximum duration to flowering (Rai *et al*., 2012) [12].

For the number of tillers at first cut (NTFC), values extended from 3.5 (SC18) to 8.5 (SC12, SC25, SC29) with an overall mean of 6.32. Number of tillers at regrowth (NTR) ranged from 1.0 to 4.0, recording an average of 1.34, while the number of nodes per tiller (NNT) varied between 3.0 (SC30) and 6.5 (SC23 and SC45) with a mean of 4.55.

Green fodder yield at first cut (kg/plot), The check registered 8.40 kg/plot, whereas the mean of crosses was considerably higher. Several hybrids such as SC3 (20.45 kg), SC4 (20.0 kg), SC6 (19.92 kg), and SC25 (20.68 kg) nearly doubled the yield over the check. This indicates that the majority of hybrids expressed strong superiority for green fodder yield at the first Cut. These results are similar to earlier studies in forage yields of top cross hybrids (Gupta *et al*., 2015) [11].

Hybrids like SC3 (10.20 kg), SC6 (9.56 kg), and SC25 (9.26 kg) showed more increase dry fodder yield at first cut over the check. Almost all crosses surpassed the check, highlighting their advantage in maintaining higher dry matter accumulation. Results are similarly to earlier investigation (Gupta *et al*. 2022) [3]. Green Fodder Yield at Second Harvest (GFY-2, kg/plot), Outstanding entries included SC6 (16.83 kg), SC14 (15.23 kg), SC32 (15.79 kg), and SC42 (15.23 kg), demonstrating their ability to sustain high fodder productivity at the ratoon stage. Dry Fodder Yield at Second Harvest (DFY-2, kg/plot), hybrids such as SC6 (8.50 kg), SC4 (6.98 kg), SC12 (6.55 kg), SC14 (6.76 kg), and SC42 (6.87 kg) produced higher yields. More dry fodder yields at second cut were related to the previous investigations (Gupta *et al*., 2018) [9].

Total Green Fodder Yield (TGFY, kg/plot), Hybrids like SC6 (36.75 kg), SC4 (33.82 kg), SC3 (33.24 kg), SC25 (33.27 kg), and SC42 (31.78 kg) exhibited more than double the check yield. This trend signifies that hybrid vigour was strongly expressed in cumulative green fodder production. Earlier studies stated that single cross hybrids are out performed than their parents in forage pearl millet (Kandarkar *et al*., 2023) [13].

The Total Dry Fodder Yield (TDFY, kg/plot, Hybrids such as SC6 (18.06 kg), SC4 (16.03 kg), SC42 (15.72 kg), and SC12 (15.25 kg) produced three to four times more dry fodder than the check. This clearly reflects the superiority of hybrids in terms of total dry matter production. Dry matter accumulation in single crosses over the parental lines is accordance with previous research work (Gupta *et al*., 2018) [9].

Table 1: ANOVA for forage parameters of 45 single crosses along with 5 checks and 10 parental lines.

Source of variation	DF	Mean sum of squares													
		PH-1		PH-2		DFF		NT-1		NTR		NNT		NL	
Replications	1	56.846	*	9.476		9.257		0.579		2.064	*	0.029		0.413	
Treatments	69	683.335	**	393.996	**	32.984	**	2.283	*	0.876	*	2.027	*	2.370	**
Error	69	10.063		2.968		7.938		1.115		0.441		1.318		0.175	
Total	139	344.613		197.122		20.380		1.691		0.669		1.661		1.266	

Source of variation	DF	Mean sum of squares													
		LSR		GFY-1		DFY-1		GFY-2		DFY-2		TGFY		TDFY	
Replications	1	0.056		11.886		0.045		3.292		0.230		19.780		0.071	
Treatments	69	0.106	**	441.014	**	101.612	**	264.839	**	66.670	**	1272.265	**	301.087	**
Error	69	0.019		4.631		0.849		4.424		2.743		10.855		4.067	
Totals	139	0.062		221.305		50.863		133.686		34.458		637.087		151.480	

* Significant at 5% level, ** Significant at 1% level

PH-1-Plant height in first cut (cm), PH-2-Plant height in second cut (cm), DFF-Days to 50% flowering, NT-1-Number of tillers per plant in first cut, NNT-Number of new tillers, NL-Number of leaves per plant, LSR-Leaf to stem ratio, GFY-1-Green fodder yield in first cut tonnes per hectare, DFY-1-Dry fodder yield in first cut tonnes per hectare, GFY-2-Green fodder yield in second cut tonnes per hectare, DFY-2-Dry fodder yield in second cut tonnes per hectare, TGFY-Total green fodder yield tonnes per hectare, TDFY-Total dry fodder yield.

Table 2: ANOVA for forage yield parameters of 40 TWC hybrids along with parental lines (20 F_1s, 2 inbred lines).

Source of variation	DF	Mean sum of squares						
		PH-1	PH-2	DFF	NT-1	NTR	NNT	NL
Replications	1	13.644	13.657	2.000	2.00*	0.031	4.500	0.272
Treatments	69	293.811**	320.168**	18.405**	2.781	0.786***	2.805***	2.675**
Error	69	9.844	7.456	1.302	0.810	0.825	0.960	0.230
Total	139	150.739	162.630	9.791	1.797	0.799	1.903	1.443

Source of variation	DF	Mean sum of squares						
		LSR	GFY-1	DFY-1	GFY-2	DFY-2	TGFY	TDFY
Replications	1	0.163	17.964	0.324	10.482	2.848	1.001	5.092
Treatments	69	0.259**	163.816**	39.126**	145.356**	39.822**	453.475 **	122.691**
Error	69	0.068	13.994	0.949	19.850	6.147	35.305	7.491
Total	139	0.164	88.346	19.883	82.035	22.826	242.473	64.618

* Significant at 5% level, ** Significant at 1% level

PH-1-Plant height in first cut (cm), PH-2-Plant height in second cut (cm), DFF-Days to 50% flowering, NT-1-Number of tillers per plant in first cut, NNT-Number of new tillers, NTR-Number of tillers regenerated, NL-Number of leaves per plant, LSR-Leaf to stem ratio, GFY-1-Green fodder yield in first cut tonnes per hectare, DFY-1-Dry fodder yield in first cut tonnes per hectare, GFY-2-Green fodder yield in second cut tonnes per hectare, DFY-2-Dry fodder yield in second cut tonnes per hectare, TGFY-Total green fodder yield tonnes per hectare, TDFY-Total dry fodder yield tonnes per hectare.

The evaluation of 40 three-way cross hybrids (TWCHs) revealed substantial genetic variability across growth and forage yield traits. Plant height at both cuts was considerably higher in most hybrids compared to the standard check Raftaar (195.63 cm at first cut and 161.50 cm at second cut) and their parents, indicating strong vegetative vigour and better regrowth potential. Hybrids such as TWCH6 (234.75 cm, 219.09 cm), TWCH18 (229.87 cm, 219.03 cm), and TWCH13 (215.17 cm) consistently recorded superior plant height, surpassing the Single cross by moderate margin. This result near to previous work done in forage pearl millet (Gupta *et al*., 2022) [3].

Variation in flowering time was also evident, ranging from 49.5 days (TWCH8) to 64.5 days (TWCH40), with a mean of 55.6 days, closely matching Raftaar (55.5 days) and most of the single crosses. Earliness was particularly noted in TWCH8 (49.5 days), TWCH4 (51.0 days), and TWCH36 (52.0 days), offering better adaptability under short-duration conditions. These results are in agreement with the results of previous studies (Rai *et al*. 2012) [12].

Tillering ability showed clear hybrid advantage. The number of tillers per plant (NTFC) ranged from 4.5 (TWCH29, TWCH23) to 8.5 (TWCH1, TWCH2, TWCH16. Green Fodder Yield at First Cut (GFY-1, kg/plot).

Total Green Forage Yield (TGFY, kg/plot), The standard check recorded 16.63 kg/plot, whereas hybrids showed much higher totals. The leading performers were TWCH18 (37.15 kg/plot), TWCH36 (36.56 kg/plot), TWCH33 (36.28 kg/plot), and TWCH6 (35.98 kg/plot). Hybrids like TWCH3 (33.07 kg/plot), TWCH16 (31.13 kg/plot), and TWCH21 (31.62 kg/plot) also maintained significant superiority over the check. Earlier Studies have also demonstrated that seed yield of three-way cross hybrids (involvement of three diverse inbred parents) is double as compared to single-cross hybrids in maize (Arief *et al*., 2015) and in sunflower (Jayalakshmi *et al*., 2004).

Total Dry Forage Yield (TDFY, kg/plot), Raftaar yielded 7.75 kg/plot, whereas hybrids ranged up to nearly three-fold higher. The most promising were TWCH6 (20.66 kg/plot), TWCH33 (16.51 kg/plot), TWCH21 (16.49 kg/plot), and TWCH36 (14.65 kg/plot). Other crosses such as TWCH5 (15.25 kg/plot), TWCH26 (14.94 kg/plot), and TWCH35 (14.32 kg/plot) also displayed strong dry matter accumulation (Gupta *et al*., 2022) [3].

Overall, the results demonstrated wide genetic variability among the crosses. Several hybrids such as SC12 (IIMR AVS71 × IIMR AVS98), SC25 (IIMR AVS77 × IIMR AVS98), and SC42 (IIMR AVS95 × IIMR AVS41) were superior in plant height and tillering. These crosses appear promising for further evaluation and selection in forage pearl millet improvement programs. The overall performance of the forty-five single crosses was compared with the standard check for green fodder and dry fodder yields recorded across two harvests, as well as the total yields.

Across all traits, Most of the TWCs were shown highly dominance over single cross hybrids in yield traits, both total green fodder production and dry fodder production in two cuts (first cut and second cut). The three-way cross hybrids consistently performed, confirming the significant role of hybrid vigour in enhancing biomass productivity. Among the crosses, TWCH6, TWCH18, TWCH33, TWCH36, and TWCH21 emerged as the most promising for both green and dry fodder yield, suggesting their potential for further testing and commercial use. Earlier studies have also stated that yield of three-way cross hybrids (Divergent parents) is double as compared to single-cross hybrids in maize (Arief *et al*., 2015) and in sunflower (Jayalakshmi *et al*., 2004).

Table 3: Mean performances of yield attributing traits in single crosses.

S. No	CROSS ID	PH-1	PH-2	DFF	NL	LSR	NTFC	NTR	NNT	GFY-1	DFY-1	GFY-2	DFY-2	TGFY	TDFY
1	SC1	185.72	169.41	54.5	6.55	0.75	7.5	1	4	11.705	6.03	7.71	3.295	19.415	9.325
2	SC2	192.12	189.78	55.5	6.3	0.35	5.5	2	6	11.46	5.065	6.99	3.195	18.45	8.26
3	SC3	199.85	193.67	55	8.3	0.75	4.5	1	3.5	20.45	10.195	12.785	4.26	33.235	14.455
4	SC4	202.18	191.27	53	8.7	0.55	6.5	1	4	20	9.055	13.815	6.975	33.815	16.03
5	SC5	190.23	180.11	60	7.45	0.45	5.5	1	3.5	15.41	7.47	9.41	4.91	24.82	12.38
6	SC6	198.67	192.05	57	8.5	0.5	7.5	1	3.5	19.915	9.56	16.83	8.495	36.745	18.055
7	SC7	191.65	185.48	54.5	6.85	0.75	6.5	2	4.5	16.66	6.83	11.82	6.22	28.48	13.05
8	SC8	190.00	172.23	58	6.65	0.55	7	1	5	16.15	7	11.87	6.145	28.02	13.145
9	SC9	187.37	178.88	56.5	5.3	0.45	6	1	4	14.315	7.24	7.775	4.205	22.09	11.445
10	SC10	195.99	185.24	52	5.15	0.35	7	2	5	14.55	7.1	8.36	5.27	22.91	12.37
11	SC11	216.85	198.67	57.5	9.25	1.15	5.5	1	4.5	18.44	8.92	8.375	5.035	26.815	13.955
12	SC12	217.50	198.78	53.5	6.95	1.15	8	1	3.5	16.755	8.7	12.92	6.55	29.675	15.25
13	SC13	207.62	192.75	56.5	5.1	0.45	5.5	1	4	12.615	5.77	8.045	4.945	20.66	10.715
14	SC14	201.84	195.5	51	6.3	0.55	7	2	4.5	15.735	7.965	15.225	6.76	30.96	14.725
15	SC15	199.82	195.25	58	6	0.8	6.5	1	5	12.255	5.81	10.67	5.41	22.925	11.22
16	SC16	199.63	189.69	53	5.3	0.45	8.5	1	4	10.975	5.55	8.235	5.07	19.21	10.62
17	SC17	204.91	211.17	59	6.3	0.65	5.5	1	5.5	13.215	6.55	8.405	4.145	21.62	10.695
18	SC18	191.01	185.76	54	6.55	0.55	3.5	1	3.5	15.98	8.035	7.21	3.655	23.19	11.69
19	SC19	194.92	186.89	52.5	4.85	0.55	6.5	1	5	9.9	4.21	6.915	3.895	16.815	8.105
20	SC20	199.09	184.71	56.5	7.6	0.65	5.5	4	5.5	15.15	7.795	9.21	4.91	24.36	12.705
21	SC21	201.9	192.90	54	5.85	0.4	6.5	1	6	11.185	6.055	10.955	6.045	22.14	12.1
22	SC22	189.12	178.22	55.5	4.6	0.6	5.5	2	4.5	8.82	5.075	8.225	3.99	17.045	9.065
23	SC23	194.99	190.51	53.5	6.7	0.5	7.5	1	6.5	9.92	5.905	8.835	4.15	18.755	10.055
24	SC24	193.78	184.16	55	6.65	0.65	4.5	1	4	16.935	7.325	8.8	4.285	25.735	11.61
25	SC25	211.05	192.85	47.5	8.5	1.25	8.5	1	5	20.68	9.26	12.59	5.42	33.27	14.68
26	SC27	202.76	194.65	52.5	7.15	0.4	5.5	2	4	17.65	8.43	9.01	4.41	26.66	12.84
27	SC28	204.66	190.56	56	7.05	0.35	7.5	1	4.5	17.13	8.215	14.295	6.415	31.425	14.63
28	SC29	209	191.88	57.5	5.3	0.9	6.5	1	4	12.23	5.55	7.545	4.025	19.775	9.575
29	SC30	208.98	192.39	50.5	5.65	0.75	8.5	1	4.5	16.055	7.045	10.26	4.59	26.315	11.635
30	SC31	183.03	177.71	58	6.5	0.65	7.5	1	3	12.575	5.045	5.455	3.53	18.03	8.575
31	SC32	179.73	175.02	56.5	5.3	0.65	5	2	4.5	12.355	6.42	9.955	4.45	22.31	10.87
32	SC33	195.07	187.70	56	6.35	0.7	5.5	2	3.5	14.04	7.565	15.785	5.54	29.825	13.105
33	SC34	198.8	191.12	54	7.5	0.75	7	1	4.5	11.625	5.73	11.685	5.11	23.31	10.84
34	SC35	197.52	184.78	59	6.7	0.85	6.5	1	3.5	14.885	6.315	12.645	5.4	27.53	11.715
35	SC36	197.98	187.92	53.5	7.15	1.05	5.5	1	5.5	17.835	7.95	11.2	5.22	29.035	13.17
36	SC37	192.86	177.01	58.5	6.5	0.5	7.5	1.5	4.5	11.49	6.61	10.985	5.435	22.475	12.045
37	SC38	190.07	178.24	54.5	8.3	0.6	6.5	1	4.5	9.57	4.495	7.955	3.485	17.525	7.98
38	SC39	173.07	167.41	53	5.45	0.5	6.5	2	5	10.675	5.01	9.02	3.96	19.695	8.97
39	SC40	191.21	178.44	62	8	0.85	6	1	6	14.47	7.73	7.58	3.475	22.05	11.205
40	SC41	202.11	193.27	55	6.65	0.55	6	2	5	13.91	7.53	10.76	5.24	24.67	12.77
41	SC42	189.84	187.62	50	7.4	0.35	5	1.5	4	15.54	7.23	11.43	5.38	26.97	12.61
42	SC27	211.27	200.64	57.5	8.3	1.15	6	1.5	4	16.545	8.85	15.23	6.865	31.775	15.715
43	SC28	201.69	194.22	59.5	6.3	1.15	6	1.5	4.5	12.22	5	10.85	4.58	23.07	9.58
44	SC29	213.86	195.32	55.5	8.7	1.3	6.5	1.5	5.5	15.03	8.16	10.885	5.005	25.915	13.165
45	SC30	193.28	190.15	53.5	7.85	1.0	5.5	1	6.5	14.475	6.51	10.385	5.115	24.86	11.625
46	Check (Raftaar)	197.18	172.72	64	7.7	0.9	5.5	1.5	5.0	8.4	3.05	7.65	1.9	16.05	4.95
	Range (Lowest)	173.0	167.41	47.5	4.6	0.35	3.5	1.00	3.00	8.82	4.21	5.45	3.19	16.81	7.98
	Range (Highest)	217.50	211.17	62	9.25	1.25	8.5	4.00	6.5	20.6	10.19	16.8	8.49	36.74	18.05
	GRAND MEAN	197.66	187.82	55.23	6.76	0.68	6.32	1.34	4.55	14.43	6.97	10.33	4.98	24.76	11.96
	CV (%)	0.42	0.93	5.46	7.5	10.33	12.81	13.04	12.05	4.39	3.87	6.3	10.16	3.22	5.31
	SEm	0.59	1.24	2.13	0.35	0.08	0.70	0.21	0.71	1.65	0.76	1.7	3.7	2.08	1.66

PH-1-Plant height in first cut (cm), PH-2-Plant height in second cut (cm), DFF-Days to 50% flowering, NT-1-Number of tillers per plant in first cut, NNT-Number of new tillers, NTR-Number of tillers regenerated, NL-Number of leaves per plant, LSR-Leaf to stem ratio, GFY-1-Green fodder yield in first cut tonnes per hectare, DFY-1-Dry fodder yield in first cut kg/plot, GFY-2-Green fodder yield in second cut kg/plot, DFY-2-Dry fodder yield in second cut kg/plot, TGFY-Total green fodder yield kg/plot, TDFY-Total dry fodder yield kg/plot

Table 4: Mean performances of fodder yield attributing traits in three-way cross hybrids.

S. No	CROSS ID	PH-1	PH-2	DFF	NL	LSR	NTFC	NTR	NNT	GFY-1	DFY-1	GFY-2	DFY-2	TGFY	TDFY
1	TWCH1	184.51	179.17	55.5	5.25	0.55	8.5	1.5	4.5	17.735	6.985	10.08	3.685	27.815	10.67
2	TWCH2	191.34	175.33	59.5	6.15	0.55	8.5	1.5	5.5	17.46	6.975	10.21	4.05	27.67	11.025
3	TWCH3	222.73	195.53	58.5	9.70	1.25	7.5	1	5	19.97	7.555	13.1	6.32	33.07	13.875
4	TWCH4	201.37	192.96	51	7.85	1.2	6.5	3	3.5	18.395	8.215	11.565	6.05	29.96	14.265
5	TWCH5	187.81	179.7	59.5	7.05	1.15	4.5	2	2.5	17.24	7.715	14.1	7.53	31.34	15.245
6	TWCH6	234.75	219.09	54	8.15	1.55	6.5	1.5	4.5	19.26	11.14	16.725	9.515	35.985	20.655
7	TWCH7	200.62	190.44	53	5.45	1.25	7.5	1.5	5	12.05	5.745	9.71	5.095	21.76	10.84
8	TWCH8	206.26	193.19	49.5	6.25	1.25	5.5	1	4.5	15.005	7.02	11.01	5.495	26.015	12.515
9	TWCH9	208.86	190.00	53	5.55	1.115	7	1.5	4	14.505	6.615	9.325	5.92	23.83	12.535
10	TWCH10	196.37	186.7	58	6.35	0.8	4.5	1.5	3.5	14.045	5.715	9.53	4.55	23.575	10.265
11	TWCH11	203.22	197.45	53	4.15	0.75	4.5	2	5.5	18.505	6.73	8.845	4.68	27.35	11.41
12	TWCH12	187.96	172.39	53	5.15	1	6.5	1.5	7.5	17.06	6.125	8.345	5.065	25.405	11.19
13	TWCH13	218.99	215.17	55.5	7.5	1.3	6.5	3	6.5	16.9	7.15	13.06	5.755	29.96	12.905
14	TWCH14	201.00	198.31	57.5	6.5	1.5	4.5	1	4.5	13.9	6.55	11.06	5.255	24.96	11.805
15	TWCH15	192.545	189.51	61.5	7.6	0.95	7.5	2	5.5	13.975	6.405	11.55	4.92	25.525	11.325
16	TWCH16	214.83	197.09	54.5	7	1.05	8.5	1.5	3.5	16.455	6.865	14.68	6.06	31.135	12.925
17	TWCH17	193.71	187.72	55.5	5	0.65	7.5	1.5	4	17.95	6.98	10.44	4.5	28.39	11.48
18	TWCH18	229.87	219.03	59.5	8.6	0.75	7	2	4	22.895	8.615	14.25	7.175	37.145	15.79
19	TWCH19	209.85	203.36	58.5	6.65	1	5.5	3	5.5	13.35	6.72	9.54	3.89	22.89	10.61
20	TWCH20	215.07	197.27	63.5	7.8	1.15	6.5	1.5	4.5	17.745	8.495	11.71	5.325	29.455	13.82
21	TWCH21	218.15	195.65	58.5	7.25	0.85	7.5	1.5	5.5	18.06	8.69	13.56	7.795	31.62	16.485
22	TWCH22	184.5	179.75	55	4.15	0.55	6.5	1.5	6	15.4	7.53	12.175	5.385	27.575	12.915
23	TWCH23	183.56	172.16	61.5	7.05	0.9	4.5	1	5.5	14.35	6.67	8.665	4.455	23.015	11.125
24	TWCH24	188.07	176.38	58.5	6.2	1.05	7	1	7.5	15.585	6.67	10.46	4.51	26.045	11.18
25	TWCH25	182.91	173.01	58.5	6.05	0.65	6.5	1.5	5.5	12.525	6.755	11.215	6.12	23.74	12.875
26	TWCH26	213.91	204.76	54.5	8.6	1.55	7	2.5	6	17.9	8.285	12.445	6.65	30.345	14.935
27	TWCH27	188.64	161.63	52	6.45	0.45	6.5	1.5	3.5	15.26	7.77	12.94	7.23	28.2	15
28	TWCH28	186.17	174.92	53	6.65	1.1	5.5	3	3.5	12.905	6.465	11.84	4.765	24.745	11.23
29	TWCH29	193.98	188.37	59	7.65	1.5	4.5	1	4	16.505	6.975	10.125	4.56	26.63	11.535
30	TWCH30	195.6	185.94	54	7.6	0.6	6.5	3	3.5	17.11	5.525	10.77	6.18	27.88	11.705
31	TWCH31	187.31	180.18	52	5.55	0.5	4.5	1.5	4	11.505	6.56	11.595	6.14	23.1	12.7
32	TWCH32	176.46	170.31	57.5	5.55	0.55	6.5	2	5.5	10.52	5.3	12.185	4.47	22.705	9.77
33	TWCH33	207.00	196.01	57.5	8.5	1.45	7	2	6.5	20.25	8.96	16.03	7.55	36.28	16.51
34	TWCH34	189.85	184.49	59	7.5	1	6	2.5	4	14.67	6.475	11.885	5.805	26.555	12.28
35	TWCH35	191.14	184.56	55.5	7.7	1.45	6.5	2.5	2.5	14.615	7.82	13.365	6.495	27.98	14.315
36	TWCH36	213.56	195.85	52	8.9	1.35	5.5	1.5	6	20.17	7.555	16.385	7.095	36.555	14.65
37	TWCH37	192.49	184.04	58.5	8.15	0.45	7.5	2.5	3.5	13.615	6.55	10.635	4.555	24.25	11.105
38	TWCH38	197.33	166.695	57.5	5.15	0.7	7.5	1.5	5.5	15.01	7.235	10.98	5.065	25.99	12.3
39	TWCH39	191.5	185.72	58	7.4	0.65	5	2.5	4.5	14.115	6.41	9.595	3.605	23.71	10.015
40	TWCH40	194.785	181.38	63.5	7.6	0.7	5.5	1	3.5	14.05	7.07	9.445	5.42	23.495	12.49
	Check (Raftar)	195.63	161.50	55.5	8.1	0.7	4.5	2.5	3.5	10.38	5.35	6.255	2.4	16.635	7.75
	Range (Lowest)	176.46	161.63	49.5	4.15	0.45	4.50	1.0	2.5	10.52	5.30	8.34	3.6	21.76	9.7
	Range (Highest)	234.75	219.09	63.5	9.70	1.55	8.50	3.0	7.50	22.89	11.1	16.7	9.5	37.14	20.6
	GRAND MEAN	199.46	188.03	56.47	6.83	0.96	6.36	1.80	4.73	15.96	7.13	11.62	5.6	27.59	12.75
	CV (%)	1.33	1.39	2.08	8.17	11.31	11.8	9.17	12.37	6.9	3.62	10.6	12.06	5.99	5.93
	SEm	1.88	1.84	0.83	0.39	0.18	0.62	0.62	0.71	0.78	0.18	0.87	05	1.17	053

Table 3: Mean performance of forage yield parameters of Top 10 single crosses along with check.

S. No Cross ID	Forage yield traits of Single Crosses(kg/plot)					
	GFY-1	DFY-1	GFY-2	DFY-2	TGFY	TDFY
1 SC6	19.91	9.56	16.83	8.49	36.74	18.05
2 SC4	20.00	9.05	13.81	6.97	33.81	16.03
3 SC25	20.68	9.26	12.59	5.42	33.27	14.68
4 SC3	20.45	10.20	12.79	4.26	33.23	14.46
5 SC42	16.55	8.85	15.23	6.87	31.77	15.71
6 SC27	17.13	8.21	14.29	6.42	31.43	14.63
7 SC14	15.73	7.96	15.22	6.76	30.96	14.72
8 SC12	16.75	8.70	12.92	6.55	29.68	15.25
9 SC32	14.04	7.57	15.79	5.54	29.82	13.11
10 SC35	17.84	7.95	11.20	5.22	29.04	13.17
Check Raftar	8.4	3.05	7.65	1.9	16.05	4.95

SC-Single cross DFY-1-Dry fodder yield in first cut (kg/plot), GFY-2-Green fodder yield in second cut (kg/plot), DFY-2-Dry fodder yield in second cut (kg/plot), TGFY-Total green fodder yield tonnes (kg/plot), TDFY-Total dry fodder yield (kg/plo

Table 3: Mean performance of forage yield parameters of Top 10 Three-way cross hybrids.

S. No Cross ID	Forage yield traits of Three-way cross hybrids(kg/plot)					
	GFY-1	DFY-1	GFY-2	DFY-2	TGFY	TDFY
1 TWCH18	22.895	8.615	14.25	7.175	37.14	15.79
2 TWCH6	19.26	11.14	16.725	9.515	35.98	20.65
3 TWCH36	20.17	7.55	16.38	7.09	36.55	14.65
4 TWCH33	20.25	8.96	16.03	7.55	36.28	16.51
5 TWCH3	19.97	7.55	13.10	6.32	33.07	13.87
6 TWCH5	17.24	7.71	14.10	7.53	31.34	15.245
7 TWCH21	18.06	8.69	13.56	7.79	31.62	16.48
8 TWCH16	16.455	6.86	14.68	6.06	31.13	12.92
9 TWCH26	17.90	8.28	12.44	6.65	30.34	14.93
10 TWCH20	17.745	8.49	11.71	5.32	29.45	13.82
Check Raftar	10.38	5.35	6.25	2.4	16.63	7.75

TWCH-Three-way cross hybrids DFY-1-Dry fodder yield in first cut (kg/plot), GFY-2-Green fodder yield in second cut (kg/plot), DFY-2-Dry fodder yield in second cut (kg/plot), TGFY-Total green fodder yield tonnes (kg/plot), TDFY-Total dry fodder yield (kg/plot)

4. Conclusion

The study evaluated both Single and three-way cross hybrids for variability in forage yield traits. Total 45 single crosses and 40 Three-way cross hybrids were evaluated for forage performance in two cuts. Most of the single crosses were shown great variability in traits like plant height, tillering ability and leaf stem ratio, number of leaves and fodder yields. Based on the yield traits Evaluation, Out of 40 crosses 20 crosses selected for development of three-way cross hybrids along with better inbred lines. Evaluation of three-way cross hybrids revealed that some TWC hybrids yielded near to Single cross hybrids, Some TWCs shown less yield Productivity of Three-way cross hybrids. Most of the TWCs were shown highly dominance over single cross hybrids in yield traits, both total green fodder production and dry fodder production in two cuts (first cut and second cut). This study concluded that the genetic variability among Three-way cross hybrids is higher than single crosses of forage pearl millet in forage yield production. Findings highlight the effectiveness of using three-way hybridization to combine desirable traits from multiple parents, thereby enhancing heterotic expression. This study provides a strong basis for identifying promising hybrid combinations for future breeding programs aimed at improving forage yield, quality, and sustainability in pearl millet.

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Author(s) hereby declares that no generative AI technologies such as Large Language Models (Chat GPT, COPILOT, etc) and text-to-image generators have been used during writing or editing manuscripts.

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Competing Interests

Authors have declared that no competing interests exist.

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