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Pearl millet cultivars, fertility levels and in-situ moisture-conservation practices on crop growth, yield and economics under rainfed conditions

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ABSTRACT

A two-year field experiment was conducted during the kharif seasons of 2024 and 2025 at Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, to evaluate the effects of pearl millet cultivars, fertility levels and in-situ moisture-conservation practices on growth, yield and profitability under rainfed conditions. The experiment comprised two cultivars (TMBH 2652 and KH 302), three fertility levels [100% recommended dose of fertilizer (RDF), 100% RDF + FYM at 2.5 t ha⁻¹ and 100% RDF + FYM at 5 t ha⁻¹] and four moisture-conservation practices. Pooled results showed that TMBH 2652 produced higher grain yield (27.33 q ha⁻¹) than KH 302 (25.74 q ha⁻¹). Application of 100% RDF + FYM at 5 t ha⁻¹ recorded 28.63 q ha⁻¹ grain yield, representing a 16.9% increase over RDF alone. Ridge and furrow combined with vegetative mulch at 4 t ha⁻¹ produced the highest pooled grain yield (29.48 q ha⁻¹), 22.6% higher than conventional line sowing. This practice also recorded the highest net return (₹69,288 ha⁻¹) and B:C ratio (2.84). The findings indicate that improved cultivar selection, integrated fertility management and in-situ moisture conservation can enhance pearl millet productivity and profitability under rainfed conditions.

Keywords: Rainfed agriculture, Integrated nutrient management, Farmyard manure, Ridge and furrow, Vegetative mulch

Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is an important cereal crop of arid and semi-arid regions because of its ability to withstand high temperature, low and erratic rainfall and relatively poor soil fertility. Its C₄ photosynthetic pathway, extensive root system and physiological adaptability enable the crop to produce under environments where many other cereals perform poorly. Besides its importance as food and livestock fodder, pearl millet is increasingly recognized as a climate-resilient and nutritionally important cereal (Satyavathi *et al.*, 2021; Shrestha *et al.*, 2023) [1, 2].

Despite its drought tolerance, productivity of pearl millet under rainfed conditions is often constrained by uneven rainfall and soil-moisture deficit, particularly during reproductive and grain-filling stages. In-situ moisture-conservation practices such as ridge and furrow formation and surface mulching can reduce runoff and evaporation, improve infiltration and maintain soil moisture for a longer period. Consequently, these practices may improve crop establishment, biomass production and yield formation under rainfed environments. Studies have also demonstrated improvements in pearl millet productivity through ridge-based and other moisture-conservation practices (Rathore *et al.*, 2006; Pareek *et al.*, 2018) [4, 3].

Soil fertility is another major limitation to pearl millet productivity. Although the crop can survive on relatively poor soils, realization of its yield potential requires adequate and balanced nutrient supply. Integration of organic sources such as farmyard manure (FYM) with mineral fertilizers can provide sustained nutrient availability and improve crop growth and yield. Jakhar *et al.* (2018) [5] reported significant improvement in pearl millet growth, yield attributes and productivity through integrated nutrient management.

Crop response to improved nutrient and moisture management may also vary with cultivar because pearl millet genotypes differ in tillering ability, biomass production, panicle characteristics and adaptation to environmental stress. Therefore, identification of an appropriate cultivar together with efficient fertility and moisture-management practices is important for improving rainfed production. The present study was undertaken to evaluate the effects of pearl millet cultivars, fertility levels and in-situ moisture-conservation practices on crop growth, yield and economics under rainfed conditions.

Materials and Methods

Experimental site and soil

A field experiment was conducted during the *kharif* seasons of 2024 and 2025 at the Soil Conservation and Water Management Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India. The experimental soil was sandy loam, comprising 59.2% sand, 20.8% silt and 19.8% clay. The soil had pH 7.3, electrical conductivity of 0.36 dS m⁻¹, bulk density of 1.34 Mg m⁻³, field capacity of 18.6%, organic carbon of 0.32%, available N of 179.21 kg ha⁻¹, available P of 17.87 kg ha⁻¹ and available K of 131.34 kg ha⁻¹.

Experimental design and treatments

The experiment comprised three factors: two pearl millet cultivars, three fertility levels and four moisture-conservation practices, giving a total of 24 treatment combinations. Treatments were evaluated with three replications, resulting in 72 experimental plots. Cultivars were allocated to the main plots, fertility levels to the subplots and moisture-conservation practices to the sub-subplots. The gross and net plot sizes were 5.0 × 3.6 m and 4.0 × 2.4 m, respectively.

The cultivars were TMBH 2652 (V₁) and KH 302 (V₂). The fertility treatments consisted of 100% recommended dose of fertilizer (RDF: 60 kg N, 40 kg P₂O₅ and 40 kg K₂O ha⁻¹; F₁), 100% RDF + FYM at 2.5 t ha⁻¹ (F₂), and 100% RDF + FYM at 5 t ha⁻¹ (F₃). The moisture-conservation treatments were conventional line sowing (M₁, control), ridge and furrow formation at 30 days after sowing (DAS; M₂), vegetative mulch at 4 t ha⁻¹ applied at 30 DAS (M₃), and ridge and furrow at 30 DAS combined with vegetative mulch at 4 t ha⁻¹ at 30 DAS (M₄).

Crop establishment and management

The experimental field was prepared by tractor-drawn harrowing followed by cross-cultivation and planking. Pearl millet was sown manually in opened furrows using a seed rate of 4 kg ha⁻¹ at approximately 5 cm depth. The recommended fertilizer dose was 60:40:40 kg

N:P₂O₅:K₂O ha⁻¹. The full doses of phosphorus and potassium and half of the nitrogen were applied basally, while the remaining nitrogen was top-dressed in two splits. Farmyard manure was applied according to the respective fertility treatments at 2.5 or 5.0 t ha⁻¹. Crop-management operations were carried out uniformly across treatments to maintain an optimum crop stand and minimize interference from weeds and insect pests. The crop was harvested at physiological maturity, and harvested material from each net plot was subsequently threshed, cleaned, dried and weighed for determination of yield.

Observations collected and economic analysis

Growth assessment was restricted to the traits most closely associated with yield formation. Number of tillers plant⁻¹ was recorded at 30 DAS, 60 DAS and at harvest. Dry matter accumulation was also determined at these stages. Plant material collected for dry-matter determination was dried at 65 ± 2 °C to constant weight, and dry matter was expressed as g plant⁻¹.

Yield attributes were recorded at physiological maturity. The number of earheads plant⁻¹ was determined from randomly selected plants within each plot and expressed as earheads plant⁻¹. Earhead length was measured from the base to the tip of representative earheads using a measuring scale and expressed in centimetres. For grain weight per earhead, selected earheads were harvested and threshed separately, and the recovered grain was weighed and expressed as g earhead⁻¹.

After harvest, the produce from the net plot of each treatment was weighed. Grain yield was determined after threshing and winnowing and converted from plot yield to q ha⁻¹. Biological yield was obtained from the total above-ground harvested produce and expressed on a hectare basis. Stover yield was calculated as the difference between biological yield and grain yield and expressed as q ha⁻¹. Grain, stover and biological yields are presented separately for 2024 and 2025 to show the seasonal treatment response.

Harvest index was calculated separately for every experimental plot in each year according to Donald *et al.* (1976) [6] as:

$$\text{Harvest index (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Economic feasibility of the treatments was evaluated in terms of cost of cultivation, gross return, net return and benefit-cost (B:C) ratio. Cost of cultivation was estimated separately for each treatment by accounting for the expenditure incurred on field operations and treat-

ment-specific inputs. Gross return was calculated from the monetary value of grain and stover yield at prevailing prices. Net return was calculated as:

$$\text{Net return (₹ ha}^{-1}\text{)} = \text{Gross return} - \text{Cost of cultivation}$$

Statistical analysis

The experimental data were subjected to analysis of variance according to the factorial split-plot field design following Gomez *et al.* (1984) [7]. Cultivar (A), fertility level (B) and their interaction (A × B) were tested against the main-plot error, whereas moisture-conservation practice (C) and interactions involving C were tested against the subplot error. Differences among treatment means were evaluated using the *F*-test at the 5% probability level, and critical difference (CD) at *P* = 0.05 was calculated where the corresponding *F*-test was significant. Harvest index was computed from plot-wise grain and biological yields and analysed separately for 2024 and 2025; therefore, year-wise harvest-index values are presented rather than a pooled harvest-index column. Other variables were analysed year-wise and pooled across seasons where appropriate.

The treatment structure comprised cultivar, fertility level, moisture-conservation practice, cultivar × fertility, cultivar × moisture conservation, fertility × moisture conservation and cultivar × fertility × moisture conservation effects.

Results

Growth performance

Pearl millet growth was significantly influenced by cultivar, fertility level and moisture-conservation practice in both experimental seasons. TMBH 2652 consistently exhibited greater tillering than KH 302, recording 5.30 and 5.72 tillers plant⁻¹ at harvest in 2024 and 2025, respectively, compared with 3.61 and 4.36 tillers plant⁻¹ for KH 302. Dry matter accumulation at harvest followed the same pattern, with TMBH 2652 recording 50.72 and 52.29 g plant⁻¹ compared with 45.35 and 47.50 g plant⁻¹ for KH 302. Increasing fertility through FYM integration significantly improved growth in both years. Tillers at harvest increased from 3.83 and 4.35 plant⁻¹ under 100% RDF (F₁) to 5.21 and 5.92 plant⁻¹ under 100% RDF + FYM at 5 t ha⁻¹ (F₃) in 2024 and 2025, respectively. The corresponding dry matter values increased from 46.68 and 48.40 to 49.30 and 51.52 g plant⁻¹. Among moisture-conservation practices, ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS (M₄) produced the highest tiller numbers (4.93 and 5.73 plant⁻¹) and high dry matter accumulation (49.98 and 51.17 g plant⁻¹) in 2024 and 2025, whereas conventional line sowing recorded the lowest growth values.

Yield attributes

Yield attributes responded significantly to cultivar, fertility management and moisture-conservation practices in both years. TMBH 2652 recorded 2.11 and 2.21 earheads plant⁻¹ in 2024 and 2025, respectively, compared with 1.72 and 1.83 for KH 302. Earhead length was 30.23 and 31.69 cm in TMBH 2652 versus 27.28 and 28.81 cm in KH 302, while grain weight per earhead was 12.03 and 13.15 g versus 9.52 and 10.55 g, respectively. Fertility improvement produced a progressive increase in all yield attributes. Under F₃, earheads plant⁻¹ reached 2.45 and 2.56, earhead length 29.70 and 31.19 cm, and grain weight per earhead 11.59 and 12.87 g in 2024 and 2025, respectively. Among moisture-conservation practices, M₄ recorded the highest values in both seasons: 2.43 and 2.54 earheads plant⁻¹, 30.42 and 31.90 cm earhead length, and 12.25 and 13.06 g grain weight earhead⁻¹. The lowest corresponding values occurred under conventional line sowing (M₁).

Grain and stover yield

Significant variation in grain and stover yield was observed between the two cultivars. TMBH 2652 produced grain yields of 25.70 and 28.98 q ha⁻¹ during 2024 and 2025, respectively, compared with 24.24 and 27.25 q ha⁻¹ for KH 302. TMBH 2652 also recorded higher stover yields in both seasons (53.58 and 57.00 q ha⁻¹ in 2024 and 2025, respectively) than KH 302 (48.32 and 52.83 q ha⁻¹). Grain and stover yields increased significantly with increasing fertility level. Grain yield increased from 22.97 and 26.03 q ha⁻¹ under 100% RDF in 2024 and 2025 to 26.95 and 30.32 q ha⁻¹ under 100% RDF + FYM at 5 t ha⁻¹. The corresponding stover yields increased from 49.64 and

53.48 q ha⁻¹ to 52.32 and 56.22 q ha⁻¹. A pronounced response to moisture conservation was observed in both years. Ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS produced the highest grain yields (27.88 and 31.08 q ha⁻¹) and stover yields (52.03 and 56.17 q ha⁻¹) in 2024 and 2025, respectively. Conventional line sowing recorded the lowest grain yields (22.65 and 25.44 q ha⁻¹) and stover yields (49.85 and 53.66 q ha⁻¹) in the respective seasons.

Biological yield and year-wise harvest index

TMBH 2652 recorded significantly greater biological yield than KH 302 in both seasons, with values of 79.28 and 85.98 q ha⁻¹ in 2024 and 2025, respectively, compared with 72.56 and 80.09 q ha⁻¹ for KH 302. Harvest index, calculated separately for each season, was slightly higher in KH 302 than in TMBH 2652 in both years: 33.33 versus 32.29% in 2024 and 33.95 versus 33.61% in 2025. Increasing fertility improved biomass production and harvest index. Biological yield increased from 72.62 and 79.52 q ha⁻¹ under 100% RDF to 79.27 and 86.55 q ha⁻¹ under 100% RDF + FYM at 5 t ha⁻¹ in 2024 and 2025, respectively. The corresponding harvest-index values increased from 31.64 to 33.91% in 2024 and from 32.70 to 34.97% in 2025. Among moisture-conservation practices, ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS recorded the highest biological yield in both years (79.91 and 87.24 q ha⁻¹) and the highest harvest index (34.81 and 35.55%). Vegetative mulch at 4 t ha⁻¹ at 30 DAS ranked next, with biological yields of 77.08 and 84.57 q ha⁻¹ and harvest-index values of 33.66 and 34.77% in 2024 and 2025, respectively, whereas conventional line sowing recorded the lowest biological yields (72.50 and 79.10 q ha⁻¹) and harvest indices (31.22 and 32.10%).

Table 1. Growth and yield attributes of pearl millet as influenced by cultivar, fertility and moisture-conservation practices

Treatment	Tillers plant ⁻¹ at harvest		Dry matter at harvest (g plant ⁻¹)		Earheads plant ⁻¹		Earhead length (cm)		Grain weight earhead ⁻¹ (g)	
	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025
Cultivar										
V ₁	5.30	5.72	50.72	52.29	2.11	2.21	30.23	31.69	12.03	13.15
V ₂	3.61	4.36	45.35	47.50	1.72	1.83	27.28	28.81	9.52	10.55
CD (P = 0.05)	0.591	0.646	0.90	1.56	0.238	0.293	0.65	0.89	0.256	0.595
Fertility level										
F ₁	3.83	4.35	46.68	48.40	1.29	1.38	27.81	29.29	9.94	10.96
F ₂	4.34	4.85	48.13	49.76	2.00	2.13	28.75	30.28	10.78	11.73
F ₃	5.21	5.92	49.30	51.52	2.45	2.56	29.70	31.19	11.59	12.87
CD (P = 0.05)	0.724	0.792	1.11	1.92	0.292	0.359	0.79	1.09	0.314	0.728
Moisture-conservation practice										
M ₁	3.85	4.26	46.77	48.40	1.15	1.27	27.20	28.97	9.10	10.83
M ₂	4.20	4.63	47.06	49.76	1.97	2.08	28.25	29.66	10.57	11.42
M ₃	4.85	5.53	48.34	51.52	2.10	2.20	29.14	30.48	11.16	12.10
M ₄	4.93	5.73	49.98	51.17	2.43	2.54	30.42	31.90	12.25	13.06
CD (P = 0.05)	0.842	0.546	2.11	1.64	0.392	0.400	0.77	1.12	0.546	0.524

Table 2. Grain, stover and biological yield and harvest index of pearl millet as influenced by cultivar, fertility and moisture-conservation practices

Treatment	Grain yield (q ha ⁻¹)		Stover yield (q ha ⁻¹)		Biological yield (q ha ⁻¹)		Harvest index (%)	
	2024	2025	2024	2025	2024	2025	2024	2025
Cultivar								
V ₁	25.70	28.98	53.58	57.00	79.28	85.98	32.29	33.61
V ₂	24.24	27.25	48.32	52.83	72.56	80.09	33.32	33.95
CD (P = 0.05)	1.42	0.64	1.24	1.22	1.71	1.90	0.16	0.15
Fertility level								

(continued on next page)

Treatment	Grain yield (q ha ⁻¹)		Stover yield (q ha ⁻¹)		Biological yield (q ha ⁻¹)		Harvest index (%)	
	2024	2025	2024	2025	2024	2025	2024	2025
F ₁	22.97	26.03	49.64	53.48	72.62	79.52	31.64	32.70
F ₂	24.97	27.98	50.88	55.04	75.86	83.03	32.86	33.65
F ₃	26.95	30.32	52.32	56.22	79.27	86.55	33.91	34.97
CD (P = 0.05)	1.85	0.79	1.52	1.49	2.10	2.32	0.95	0.19
Moisture-conservation practice								
M ₁	22.65	25.44	49.85	53.66	72.50	79.10	31.22	32.10
M ₂	23.37	26.53	50.80	54.68	74.17	81.22	31.53	32.67
M ₃	25.95	29.41	51.13	55.15	77.08	84.57	33.66	34.77
M ₄	27.88	31.08	52.03	56.17	79.91	87.24	34.81	35.55
CD (P = 0.05)	1.23	0.75	1.27	1.38	2.11	2.30	0.87	0.22

Note: Grain, stover and biological yields are presented separately for 2024 and 2025. Harvest index (%) was calculated plot-wise as grain yield / biological yield × 100 and is presented separately for both years. CD values are shown at P = 0.05.

Economic performance

Economic returns differed considerably among cultivars and management treatments in both seasons. The cost of cultivation was identical for the two cultivars within each year (₹34,842 ha⁻¹ in 2024 and ₹32,900 ha⁻¹ in 2025), so the yield advantage of TMBH 2652 was directly reflected in profitability. TMBH 2652 recorded gross returns of ₹94,237 and ₹108,919 ha⁻¹, net returns of ₹59,395 and ₹73,278 ha⁻¹, and B:C ratios of 2.70 and 3.05 in 2024 and 2025, respectively. The corresponding values for KH 302 were ₹87,793 and ₹102,061 ha⁻¹ gross return, ₹52,951 and ₹66,420 ha⁻¹ net return, and B:C ratios of

2.51 and 2.86. Increasing fertility increased cultivation cost but also improved monetary returns in both years. The 100% RDF + FYM at 5 t ha⁻¹ treatment incurred costs of ₹36,467 and ₹37,291 ha⁻¹ and generated the highest gross returns (₹96,904 and ₹112,248 ha⁻¹), net returns (₹60,437 and ₹74,957 ha⁻¹) and B:C ratios (2.65 and 3.01) in 2024 and 2025, respectively. Among moisture-conservation practices, ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS recorded the highest costs of cultivation (₹36,987 and ₹37,950 ha⁻¹), but also the highest gross returns (₹99,210 and ₹114,304 ha⁻¹), net returns (₹62,223 and ₹76,354 ha⁻¹) and B:C ratios (2.68 and 2.86) in 2024 and 2025, respectively.

Table 3. Economic performance of pearl millet under different treatments

Treatment	Cost of cultivation (₹ ha ⁻¹)		Gross return (₹ ha ⁻¹)		Net return (₹ ha ⁻¹)		B:C ratio	
	2024	2025	2024	2025	2024	2025	2024	2025
Cultivar								
V ₁	34,842	35642	94,237	108,919	59,395	73,278	2.70	3.05
V ₂	34,842	35642	87,793	102,061	52,951	66,420	2.51	2.86
Fertility level								
F ₁	33,137	33,909	85,135	99,001	51,998	65,092	2.57	2.92
F ₂	34,921	35,726	90,999	105,192	56,078	69,466	2.60	2.94
F ₃	36,467	37,291	96,904	112,248	60,437	74,957	2.65	3.01
Moisture-conservation practice								
M ₁	32,538	33,256	84,340	97,398	51,862	64,142	2.59	2.93
M ₂	33,644	34,432	86,762	100,961	53,118	66,529	2.58	2.93
M ₃	36,197	37,020	93,689	109,188	57,492	72,168	2.59	2.95
M ₄	36,987	37,950	99,210	114,304	62,223	76,354	2.68	3.01

Overall treatment response

Across the two experimental seasons, the results demonstrated a consistent advantage of TMBH 2652, integrated fertility management with 100% RDF + FYM at 5 t ha⁻¹, and the combined moisture-conservation practice of ridge and furrow + vegetative mulch at 4 t ha⁻¹. These treatments improved crop growth and yield attributes and resulted in greater grain productivity and economic returns compared with the corresponding lower-input or conventional treatments.

Discussion

Cultivar differences in growth, yield attributes and productivity

The significant differences observed between the two pearl millet cultivars indicate that crop performance under rainfed conditions was strongly influenced by genetic potential. TMBH 2652 produced in both seasons greater tillering, dry matter accumulation, earhead number, earhead length and grain weight per earhead than KH 302. These advantages were reflected in higher grain and stover yields in both ex-

perimental seasons. The greater grain yield of TMBH 2652 therefore appears to have resulted from its capacity to develop a larger vegetative and reproductive sink through greater tillering and superior earhead characteristics rather than from a single yield component.

Genotypic differences in rainfed pearl millet performance are well established. Pareek *et al.* (2018) [3] reported significant cultivar differences in grain yield, harvest index and water-use efficiency under rainfed conditions, with hybrid cultivars generally outperforming composites. More recently, Gupta *et al.* (2026) [8], while evaluating 20 pearl millet hybrids under rainfed conditions, demonstrated substantial variation among hybrids in effective tillers, panicle characteristics, grain yield and biological yield. These reports support the present observation that genetic differences in tillering and reproductive traits can substantially affect final productivity under moisture-limited environments.

TMBH 2652 produced greater biological yield, whereas KH 302 recorded a slightly higher harvest index in both seasons. In 2024, harvest index was 33.33% in KH 302 and 32.29% in TMBH 2652; in 2025, the corresponding values were 33.95 and 33.61%. This contrasting behaviour indicates cultivar differences in biomass produc-

tion and partitioning. TMBH 2652 maintained greater total biomass-producing capacity, whereas KH 302 allocated a slightly greater proportion of accumulated biomass to grain. The higher harvest index of KH 302 was nevertheless insufficient to offset its lower biological yield and weaker yield-component expression, so TMBH 2652 retained the advantage in grain productivity. Such cultivar-specific differences in biomass production and partitioning have also been reported in pearl millet hybrids evaluated across rainfed environments (Pareek *et al.*, 2018; Gupta *et al.*, 2026) [3, 8].

Response to integrated fertility management

The progressive improvement in crop growth with increasing fertility level emphasizes the importance of integrated nutrient management even in a crop generally regarded as tolerant of low-fertility conditions. Application of 100% RDF supplemented with FYM at 5 t ha⁻¹ (F₃) resulted in the highest tiller production and dry matter accumulation, followed by 100% RDF + FYM at 2.5 t ha⁻¹, whereas 100% RDF alone recorded the lowest values. The higher dry matter production under FYM-enriched treatments was subsequently reflected in improved earhead number, earhead length and grain weight earhead⁻¹.

Superiority of integrated nutrient management can reasonably be associated with a more sustained nutrient supply during crop growth. Mineral fertilizers provide readily available nutrients during periods of high crop demand, whereas FYM contributes nutrients more gradually and may improve the soil environment in ways that favour root activity and nutrient acquisition. Consequently, the simultaneous availability of inorganic and organic nutrient sources can maintain vegetative growth for a longer period and promote the formation and development of reproductive sinks. Similar improvements in plant growth, tillering, dry matter accumulation and yield attributes of pearl millet under integrated nutrient management have been reported by Singh *et al.* (2013) [9] and Jakhar *et al.* (2018) [5]. Singh *et al.* found combinations of organic and inorganic N sources superior to several sole-source treatments, while Jakhar *et al.* reported marked improvements in tillering, dry matter, ear characteristics and grain yield under integrated fertility management.

The grain-yield response further demonstrates the agronomic advantage of supplementing the recommended fertilizer dose with organic manure. Addition of FYM at 5 t ha⁻¹ increased pooled grain yield from 24.50 q ha⁻¹ under 100% RDF alone to 28.63 q ha⁻¹, representing an increase of approximately 16.9%. Stover yield followed the same positive trend. Harvest index also increased consistently with fertility level: from 31.64% under 100% RDF to 33.92% under 100% RDF + FYM at 5 t ha⁻¹ in 2024, and from 32.71 to 34.98% in 2025. The intermediate fertility treatment, 100% RDF + FYM at 2.5 t ha⁻¹, recorded harvest-index values of 32.87 and 33.65% in 2024 and 2025, respectively.

Comparable responses have been observed under other rainfed pearl millet environments. Kumar *et al.* (2004) [10] reported significant improvement in pearl millet yield through moisture conservation combined with FYM and fertilizer N, while Rathore *et al.* (2006) [4] demonstrated substantial improvement in growth, productivity and resource-use efficiency through integrated nutrient management. Jakhar *et al.* (2018) [5] likewise recorded higher grain and straw yields when nutrient management included balanced mineral nutrition and biological/organic components. Collectively, these studies indicate that pearl millet responds strongly to improved nutrient availability even under rainfed conditions, provided that sufficient moisture is available to facilitate nutrient uptake.

Influence of moisture-conservation practices

Among the agronomic factors evaluated, moisture conservation produced a particularly clear response. Ridge and furrow combined with vegetative mulch (M₄) consistently enhanced tillering, dry matter accumulation and yield attributes compared with conventional line sowing. Vegetative mulch alone generally ranked second, while ridge and furrow alone produced an intermediate response. This ordering sug-

gests that the two practices may act through complementary mechanisms: ridge-furrow configuration favours collection and infiltration of rainfall, whereas surface mulch reduces direct evaporation from the soil surface and moderates the soil microenvironment. Their combined use therefore likely maintained a more favourable root-zone moisture regime during intermittent dry periods.

Previous research strongly supports this response. Shekhawat *et al.* (2015) [11] reported that vegetative mulch applied at 30 DAS significantly increased pearl millet growth, yield attributes, grain yield and stover yield under dryland conditions, with ridge and furrow also performing better than conventional management. Pareek *et al.* (2018) [3] similarly found that ridging improved soil moisture status, grain yield and straw yield under rainfed conditions. Earlier work by Jat *et al.* (2000) [12] also showed that in-situ moisture-conservation practices, particularly mulch-based treatments, improved growth and yield of rainfed pearl millet.

Greater reproductive development under M₄ is particularly important. The treatment produced more earheads plant⁻¹, longer earheads and greater grain weight per earhead than conventional line sowing. Maintenance of favourable moisture availability during reproductive development can help sustain assimilate production and reduce the restrictions imposed by intermittent water deficits on panicle growth and grain development. Consequently, improved moisture conditions during vegetative growth were translated into a greater reproductive sink at maturity.

Grain-yield response provides strong evidence of the practical value of this approach. Pooled grain yield increased from 24.04 q ha⁻¹ under conventional line sowing to 27.68 q ha⁻¹ with vegetative mulch and 29.48 q ha⁻¹ with ridge and furrow plus mulch, corresponding to a 22.6% advantage of M₄ over M₁. This magnitude of response agrees closely with recent findings of Gourav *et al.* (2026) [13], who reported grain-yield increases of approximately 17.8–25.5% from crop-residue mulching in pearl millet under restricted water availability. Their study further showed that residue management improved both crop productivity and profitability, reinforcing the importance of surface residue as a water-conservation strategy.

Positive response of stover yield is also relevant because pearl millet is an important dual-purpose crop. Although differences in stover yield among moisture treatments were smaller than those in grain yield, ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS maintained the highest stover yield in both 2024 (52.03 q ha⁻¹) and 2025 (56.17 q ha⁻¹). This suggests that moisture conservation supported both vegetative biomass production and reproductive growth instead of merely altering biomass partitioning. Similar simultaneous improvements in grain and fodder productivity under ridging or mulching have been reported by Shekhawat *et al.* (2015) [11] and Pareek *et al.* (2018) [3].

Relationship between growth, yield attributes and final yield

Treatment effects on grain yield were consistent with their effects on crop growth and yield components. Treatments producing greater tiller numbers and dry matter also generally produced more earheads, longer panicles and heavier grain earhead⁻¹. The resulting increase in grain yield therefore appears to have arisen through the cumulative improvement of several yield-forming processes rather than through a single dominant component.

This relationship is agronomically important under rainfed environments because early improvement in vegetative growth alone does not necessarily ensure higher grain yield unless assimilates are effectively converted into reproductive structures. In the present experiment, 100% RDF + FYM at 5 t ha⁻¹ and ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS enhanced growth as well as reproductive attributes and also recorded the highest harvest index within their respective factors in both seasons. Thus, the additional biomass produced under improved fertility and moisture management was accompanied by improved allocation to economic yield. Integrated nutrient management has similarly been shown to improve both vegetative growth and grain-forming attributes in rainfed pearl

millet (Singh *et al.*, 2013; Jakhar *et al.*, 2018) [9, 5], while residue mulching has recently been reported to enhance growth, yield components and final productivity under limited-water conditions (Gourav *et al.*, 2026) [13].

The relatively stronger effect of moisture conservation on grain yield than on stover yield also suggests that conserving water during critical stages may have supported reproductive development and grain filling disproportionately. This interpretation is consistent with the year-wise harvest-index response: vegetative mulch at 4 t ha⁻¹ at 30 DAS recorded 33.67 and 34.77% in 2024 and 2025, respectively, while ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS recorded 34.81 and 35.55%, compared with 31.22 and 32.11% under conventional line sowing. However, direct confirmation of the underlying water-use mechanism requires the soil-moisture and crop-water-use measurements addressed in the moisture-focused companion paper; therefore, the present interpretation remains linked to the observed crop responses rather than being presented as direct evidence of water-use processes.

Economic implications

Agronomic superiority was also reflected in economic performance in both seasons. Because cultivation costs were identical for the two cultivars within each year, the higher productivity of TMBH 2652 translated directly into greater gross and net returns and a higher B:C ratio. Its net return increased from ₹59,395 ha⁻¹ in 2024 to ₹76,019 ha⁻¹ in 2025, compared with ₹52,951 and ₹69,161 ha⁻¹, respectively, for KH 302. The corresponding B:C ratios were 2.70 and 3.05 for TMBH 2652 and 2.50 and 2.86 for KH 302, indicating a consistent economic advantage of the higher-yielding cultivar in both seasons.

The addition of FYM increased production costs, but the accompanying yield improvement was sufficient to compensate for the additional expenditure in both years. The 100% RDF + FYM at 5 t ha⁻¹ treatment incurred the highest fertility-related cultivation cost (₹36,467 ha⁻¹ in 2024 and ₹37,291 ha⁻¹ in 2025), yet it also produced the highest net returns of ₹60,437 and ₹74,957 ha⁻¹ and B:C ratios of 2.65 and 3.01, respectively. This demonstrates that evaluation of fertility treatments solely on input cost can be misleading; the additional investment is economically justified when the resulting improvement in productivity exceeds the added cost. Similar benefits of integrated nutrient management for pearl millet productivity and economic returns have been documented by Jakhar *et al.* (2018) [5], and favourable profitability from balanced organic-inorganic nutrient strategies has also been reported under rainfed environments.

A similar pattern was evident for moisture conservation. Ridge and furrow at 30 DAS + vegetative mulch at 4 t ha⁻¹ at 30 DAS had the highest cultivation cost in both seasons (₹36,987 ha⁻¹ in 2024 and ₹37,950 ha⁻¹ in 2025), but it also generated the highest gross returns (₹99,210 and ₹114,304 ha⁻¹), net returns (₹62,223 and ₹76,354 ha⁻¹) and B:C ratios (2.68 and 3.01), respectively. The economic advantage therefore arose because the yield benefit exceeded the additional cost of establishing ridges and applying mulch. Shekhawat *et al.* (2015) [11] likewise found that improved moisture-conservation practices enhanced net returns and benefit:cost ratio in dryland pearl millet, while Choudhary *et al.* (2016) [14] reported greater profitability from crop-residue-based moisture management compared with an unmulched flat bed. Recent evidence from Gourav *et al.* (2026) [13] further confirms that crop-residue mulching can simultaneously improve pearl millet productivity and economic returns.

Agronomic significance

Taken together, the two-year results demonstrate that cultivar selection, nutrient management and moisture conservation are all important determinants of rainfed pearl millet productivity. Among the respective main effects, TMBH 2652 was superior for biomass and grain production, supplementation of 100% RDF with FYM at 5 t ha⁻¹ produced the strongest fertility response, and ridge-and-furrow combined with vegetative mulch at 4 t ha⁻¹ produced the highest productivity and profitability among the moisture-conservation practices.

These findings are particularly relevant to rainfed pearl millet because nutrient availability and soil-water availability are closely linked. Fertilizer-derived nutrients cannot be used efficiently when crop water supply restricts nutrient movement and root activity, while improved moisture availability is unlikely to realize its full productive benefit when nutrient supply limits canopy and reproductive development. Previous research has likewise demonstrated beneficial responses of pearl millet to both modified planting/moisture-conservation practices and integrated nutrient management (Kumar *et al.*, 2004; Rathore *et al.*, 2006) [10, 4].

However, the superiority of TMBH 2652, F_3 and M_4 reported here represents the individual main effects of these factors. A recommendation for their specific three-factor combination should be made only after examining the cultivar × fertility × moisture-conservation interactions from the appropriate split/split-split plot analysis. This distinction is important for avoiding an unsupported claim of treatment-combination superiority.

Conclusion

The results demonstrated that cultivar, fertility management and moisture-conservation practices significantly influenced the productivity of rainfed pearl millet in both experimental seasons. TMBH 2652 performed better than KH 302 for tiller production, dry-matter accumulation, earhead characteristics and grain yield. Grain yield of TMBH 2652 was 25.70 and 28.98 q ha⁻¹ in 2024 and 2025, respectively, compared with 24.24 and 27.25 q ha⁻¹ for KH 302. Its superiority was associated with greater biomass production and better expression of yield attributes. Similar genotypic variation in pearl millet productivity under rainfed conditions has been reported by Pareek *et al.* (2018) [3] and Gupta *et al.* (2026) [8].

Integrated fertility management considerably improved crop growth and yield. Application of 100% RDF + FYM at 5 t ha⁻¹ recorded the highest tiller number, dry-matter accumulation, earhead number, earhead length and grain weight earhead⁻¹. Consequently, pooled grain yield increased from 24.50 q ha⁻¹ with 100% RDF alone to 28.63 q ha⁻¹ with 100% RDF + FYM at 5 t ha⁻¹, representing an increase of about 16.9%. The positive response may be associated with the combined availability of readily available nutrients from mineral fertilizers and gradual nutrient release from FYM, which favoured vegetative growth and reproductive development. Comparable improvements in pearl millet growth and productivity with integrated nutrient management have been reported by Rathore *et al.* (2006) [4] and Jakhar *et al.* (2018) [5].

Moisture conservation exerted a pronounced effect on pearl millet performance in both years. Ridge and furrow at 30 DAS combined with vegetative mulch at 4 t ha⁻¹ at 30 DAS produced better growth and yield attributes than the other moisture-management practices and recorded grain yields of 27.88 and 31.08 q ha⁻¹ in 2024 and 2025, respectively, compared with 22.65 and 25.44 q ha⁻¹ under conventional line sowing. The improvement can be associated with better conservation of rainfall in the root zone, increased infiltration and reduced evaporation losses from the soil surface. Vegetative mulch alone also improved productivity, indicating the importance of minimizing soil-water losses under rainfed conditions. Similar benefits of ridge-furrow systems and mulching in pearl millet have been reported by Shekhawat *et al.* (2015) [11], Choudhary *et al.* (2016) [14] and Pareek *et al.* (2018) [3].

The increases in grain yield were supported by consistent improvements in yield-forming characters during both seasons. Ridge and furrow at 30 DAS combined with vegetative mulch at 4 t ha⁻¹ at 30 DAS recorded 2.43 and 2.54 earheads plant⁻¹, earhead lengths of 30.42 and 31.90 cm, and grain weights of 12.25 and 13.06 g earhead⁻¹ in 2024 and 2025, respectively. Conventional line sowing recorded lower corresponding values of 1.15 and 1.27 earheads plant⁻¹, 27.20 and 28.97 cm earhead length, and 9.10 and 10.83 g grain weight earhead⁻¹. The year-wise consistency of these responses indicates that improved crop growth was effectively translated into greater reproductive development and final yield.

Economic performance followed the same trend as grain productivity. TMBH 2652 recorded greater net returns and B:C ratio than KH 302. Among fertility levels, 100% RDF + FYM at 5 t ha⁻¹ produced the highest net return (₹67,697 ha⁻¹) and B:C ratio (2.83). Similarly, ridge and furrow combined with vegetative mulch produced the highest net return (₹69,288 ha⁻¹) and B:C ratio (2.84) among moisture-conservation practices. Thus, the additional expenditure on FYM and moisture conservation was compensated by increased crop productivity and monetary returns.

Overall, the study indicates that selection of a productive cultivar, integrated use of FYM with recommended fertilizers and effective in-situ moisture conservation can substantially improve the productivity and profitability of rainfed pearl millet. However, these conclusions represent the main effects of the experimental factors; recommendations regarding a specific cultivar × fertility × moisture-conservation combination should be based on the corresponding interaction analysis.

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