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Effect of crop residue and phosphorus management strategies on the performance of pearl millet (*Pennisetum glaucum*) under limited irrigation conditions

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ABSTRACT

Irrigation water availability is declining which is becoming a challenge to productivity even in drought tolerant crops like pearl millet [*Pennisetum glaucum* (L.) R. Br.]. Hence, a field experiment was conducted to evaluate the effects of crop residue mulching, phosphorus fertilisation and microbial inoculation [Phosphorus solubilising bacteria (PSB) and arbuscular mycorrhizal fungi (AMF)] on growth, yield and economics of pearl millet under limited irrigation during rainy (*kharif*) season of 2022 and 2023 at ICAR-Indian Agricultural Research Institute, New Delhi. The study followed a split-plot design (SPD) with three mulching levels (no mulch, 2 t/ha and 3 t/ha) and four phosphorus treatments [control, 100% RDP (Recommended dose of phosphorus), 75% RDP + PSB + AMF and 50% RDP + PSB + AMF]. Crop residue mulching significantly improved growth and yield attributes, with 3 t/ha mulch outperforming control by increasing grain yield by 17.8–25.5% across years. Integrated nutrient management showed pronounced benefits, where 75% RDP combined with PSB and AMF resulted in the highest growth parameters and yield, improving grain yield by 16.9–19.7% over control, along with superior economic returns. The results demonstrated that residue mulching coupled with reduced phosphorus application and microbial inoculants enhances phosphorus use efficiency, crop productivity and profitability. This approach offers a sustainable and resource-efficient nutrient management strategy for pearl millet cultivation, reducing dependence on chemical fertilisers while maintaining high yields. Future adoption of such bio-integrated nutrient technologies can support climate-resilient agriculture and improve soil health in semi-arid regions.

Keywords: AMF, Integrated nutrient management, Phosphorus application rate, PSB

Crop residue burning, a prevalent practice in India, contributes significantly to environmental pollution and climate change through the emission of greenhouse gases such as CO_2, CO, CH_4, N_2O and SO_2, along with particulate matter (Gadde *et al.* 2009). This practice also results in substantial nutrient losses and deterioration of soil health. In contrast, conservation agriculture (CA)-based practices, including residue retention, mulching, reduced tillage and crop diversification, have demonstrated significant potential in improving soil physical, chemical and biological properties, enhancing water retention and increasing crop productivity (Thierfelder *et al.* 2015, Meena *et al.* 2016). Residue mulching, in particular, plays a crucial role in reducing evaporation losses, moderating soil temperature and improving moisture availability in rainfed systems. Kumar *et al.* (2024) reported that crop residue mulching combined with Pusa decomposer (C_2) significantly improved growth and yield attributes of pearl millet [*Pennisetum glaucum* (L.) R. Br.] over no mulching. They further observed that application of 40 kg K_2O/ha along with potassium solubilising bacteria (KSB) markedly enhanced plant height, ear head length and grain yield compared to control.

Phosphorus (P) is a critical macronutrient involved in key physiological processes such as energy transfer, photosynthesis, root development and grain formation. However, its availability in soils is often limited due to fixation and low solubility, resulting in poor use efficiency (Rao *et al.* 2015). Conventional phosphorus fertilisation alone is often inefficient and environmentally unsustainable. Emerging strategies such as integrated nutrient management, including the use of phosphorus-solubilising bacteria (PSB) and arbuscular mycorrhizal fungi (AMF), have shown promise in enhancing phosphorus availability and

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uptake. PSB mobilise insoluble phosphorus through organic acid production, while AMF improves nutrient and water absorption through extensive hyphal networks (Smith and Read 2008, Bindraban *et al.* 2020). Their synergistic interaction has been reported to improve phosphorus use efficiency, crop productivity and soil health under resource-constrained conditions. Declining water availability further exacerbates productivity challenges in rainfed agriculture. In India, per capita water availability has decreased from 5,177 m^3 in 1951 to 1,508 m^3 in 2014 and is projected to decline to 1,235 m^3 by 2050 (Sufian *et al.* 2020). Under such conditions, even drought-tolerant crops like pearl millet experience yield reductions due to intermittent moisture stress. Therefore, integrating water conservation practices such as residue mulching with efficient nutrient management is essential for sustaining productivity in dryland ecosystems (Rockstrom *et al.* 2010). Although individual benefits of residue mulching and biofertiliser-mediated phosphorus management are well documented, limited studies have evaluated their interactive effects under pearl millet cultivation, particularly under limited irrigation conditions. Therefore, the present study was carried out to understand these interactions which are crucial for developing resource-efficient and climate-resilient production systems.

MATERIALS AND METHODS

Experimental materials: A field experiment was conducted during rainy (*kharif*) season of 2022 and 2023 at the research farm of ICAR-Indian Agricultural Research Institute (28.35°N, 77.12°E; at an elevation of 228.6 m amsl), New Delhi. The mean maximum temperature varied from 34.66–34.5°C and mean minimum temperature from 28.8–26.4°C for *kharif* pearl millet during respective years. The experimental soil had a *p*H 7.88, EC 0.19 dS/m, organic carbon content 0.39%, 143 kg/ha N, 21.8 kg/ha P, 236 kg/ha K and bulk density 1.51 g/cc, as measured using standard procedures (Datta *et al.* 2017). The experiment was designed in a split-plot arrangement with 12 treatment combinations and three replications. Main plot treatments included: M_1 (No mulch control), M_2 (Crop residue mulching @2 t/ha) and M_3 (Crop residue mulching @3 t/ha). Subplot treatments included four phosphorus levels: S_1 (No phosphorus), S_2 [100% RDP (Recommended dose of phosphorus)], S_3 (75% RDP + PSB + AMF) and S_4 (50% RDP + PSB + AMF). Pearl millet variety 'Pusa Composite 701' was planted in July using a turbo-seeder at a seed rate of 4 kg/ha, with spacing of 45 cm × 15 cm. Fertiliser was applied according to the treatment combinations, with a recommended dose i.e. 60:40:40 kg N, P_2O_5 and K_2O/ha. The full doses of P and K, along with half of the nitrogen were applied as basal, while the remaining nitrogen was applied in two equal splits: 25% at the knee-high stage and 25% at ear-head initiation. Nutrient sources included urea for nitrogen, diammonium phosphate (DAP) for phosphorus and muriate of potash (MOP) for potassium. Seeds were treated with PSB @25 g/kg seed (carrier-based formulation containing ~10^8 CFU/g), equivalent to approximately 250 g/ha seed requirement. AMF were applied as soil inoculum @10 kg/ha (containing ~100–120 infective propagules/g) and incorporated in the root zone at the time of sowing. Wheat crop residue, sourced from the preceding wheat crop, was chopped (5–7 cm length), sun-dried and applied uniformly on the soil surface immediately after sowing as per treatment (2 and 3 t/ha). For weed management, pendimethalin @1.0 kg a.i./ha applied as pre-emergence herbicides at one day after sowing (DAS) using 500 L water/ha.

Growth and yield attributes: Growth and yield attributes were recorded following standard procedures (Rana *et al.* 2014). Measurements such as plant height, number of effective tillers/m row length and dry matter production were taken at 30, 60 DAS and harvest stage. The number of tillers was counted from a 1 m row length using a meter scale. After crop harvest, five tagged earheads from each plot and replication were selected to measure earhead length (cm) and girth (cm). Test weight (g) per earhead was determined at 12% moisture content using an electronic balance.

Economics: The economic evaluation of the treatments was conducted by considering both the cost of inputs and the returns generated from outputs, including grain and stover yields. Based on these data, gross returns, net returns and benefit-cost ratio for each treatment were calculated using the following formulae:

$$\text{Gross returns (₹/ha)} = \text{Economic yield (t/ha)} \times \text{Market price of produce (₹/t)}$$

$$\text{Net returns (₹/ha)} = \text{Gross returns (₹/ha)} - \text{Cost of cultivation (₹/ha)}$$

$$\text{Benefit: cost ratio} = \frac{\text{Net returns (₹/ha)}}{\text{Cost of cultivation returns (₹/ha)}}$$

Statistical analysis: Data analysis was conducted using split 3 × 4 treatments analysis (Compatibility Model) Excel to compare treatment effects with the control. A significance level of $p \leq 0.05$ was applied to assess statistical significance.

RESULTS AND DISCUSSION

Growth attributes: Crop residue mulching and varying phosphorus application rates in combination with PSB and AMF had a significant influence on the growth parameters of pearl millet at 30 and 60 DAS as well as at harvest during both years of the study (Table 1). At 60 DAS, plant height was significantly greater under treatments M_2 and M_3 compared to the control (M_1) across both years. However, no significant differences in plant height were observed among treatments at the harvest stage. In terms of phosphorus management, treatment S_3 (75% RDP + PSB + AMF) recorded significantly higher plant height at all growth stages compared to the control (S_1). The increase under S_3 over S_1 was 7.54% and 9.85% at 30 DAS, 2.77% and 3.24% at 60 DAS and 2.10% and 2.54% at harvest during 2022 and 2023, respectively. However, S_3 was statistically at par with S_2 (100% RDP) and S_4 (50% RDP + PSB + AMF) at all observation stages, indicating comparable performance among these treatments. All three treatments

Table 1 Effect of crop residue mulching, phosphorus application rate, PSB and AMF on growth attributes of pearl millet during 2022 and 2023

Treatments	Plant height (cm)						Number of tillers/m row length				Leaf area index (LAI)			
	30 DAS		60 DAS		At harvest		60 DAS		At harvest		30 DAS		60 DAS	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Crop residue management														
M_1	43.2	43.6	217	218	238	239	19.8	21.1	20.1	20.1	2.52	2.68	4.02	3.95
M_2	44.6	44.9	221	222	241	241	21.8	22.6	21.6	22.1	3.13	3.18	4.52	4.60
M_3	45.6	46.2	222	222	242	242	22.8	23.7	22.8	22.8	3.27	3.33	4.76	4.83
SEM±	0.72	0.55	1.1	0.53	1.27	1.37	0.6	0.4	0.7	0.6	0.08	0.07	0.07	0.07
LSD (p=0.05)	NS	2.15	4.2	2.09	NS	NS	2.4	1.6	NS	2.2	0.32	0.29	0.27	0.29
Phosphorus management														
S_1	42.4	42.6	216	216	237	236	19.3	20.3	19.3	19.6	2.29	2.31	3.67	3.63
S_2	45.1	45.3	221	223	243	243	22.2	23.6	22.4	23.0	3.14	3.20	4.63	4.69
S_3	45.6	46.8	222	223	242	242	22.8	23.3	22.7	22.4	3.47	3.55	4.89	4.93
S_4	44.8	45.0	220	222	241	242	21.7	22.6	21.4	21.7	3.00	3.19	4.55	4.60
SEM±	0.70	0.6	1.41	1.04	1.30	1.44	0.8	0.6	0.8	0.6	0.05	0.07	0.07	0.07
LSD (p=0.05)	2.07	1.7	4.18	3.09	3.87	4.27	2.5	1.9	2.4	1.9	0.15	0.20	0.20	0.22

DAS, Days after sowing; LSD, Least significant difference. Treatment details are given under Materials and Methods.

(S_2, S_3 and S_4) were significantly superior to the control (S_1). The comparable performance of S_3 with S_2 suggests that 25% reduction in phosphorus fertiliser can be compensated effectively through PSB and AMF inoculation, enhancing phosphorus availability and uptake. Similarly, the statistical parity between S_3 and S_4 indicates that even at reduced phosphorus levels (50% RDP), microbial inoculation sustains plant growth by improving root proliferation and nutrient acquisition. This highlights the synergistic role of bio-inoculants in improving phosphorus use efficiency and reducing dependence on chemical fertilisers, thereby supporting sustainable nutrient management in pearl millet. The use of crop residues as mulch contributed positively to plant growth by conserving soil moisture, reducing evaporation losses, limiting surface runoff and suppressing weed growth. This created a more favourable micro-environment for crop development by minimising nutrient competition and enhancing moisture availability.

Phosphorus is essential for pearl millet growth, promoting energy transfer, root development and nutrient uptake. It enhances plant height by supporting cell division, photosynthesis and overall plant vigour. This statement is consistent with Angel *et al.* (2023), who highlighted the crucial role of phosphorus in enhancing the efficiency of nutrient uptake by extensive root systems under sufficient nutrient conditions.

Under crop residue management practices, the highest number of tillers/m row length in pearl millet was observed at 60 DAS and at harvest under treatment M_3. This treatment was statistically comparable to M_2 in both 2022 and 2023. At 60 DAS, M_3 resulted in a significantly higher number of tillers, with increases of 15.2% in 2022 and 12.3% in 2023 compared to the control. Additionally, at harvest in 2023, the tiller count under M_3 was 13.4% higher than that of the control.

Among the phosphorus management treatments, the number of tillers/m row length at both 60 DAS and at harvest was statistically similar between treatments S_2 and S_3. These treatments showed significant increases over the control (S_1) with S_2 and S_3 recording 15.0% and 18.1% more tillers at 60 DAS and 16.1% and 18.7% more tillers at harvest, respectively, during 2022. In 2023, tiller numbers were 16.3% and 14.8% higher at 60 DAS and 17.3% and 14.3% higher at harvest under S_2 and S_3, respectively, compared to S_1. Additionally, treatment S_4 was statistically at par with S_2 and S_3 in both study years. Residue mulching positively influences the number of tillers in pearl millet by improving soil moisture retention, reducing soil temperature fluctuations and enhancing nutrient availability. The mulch layer acts as a barrier, reducing water evaporation and maintaining consistent soil moisture, which is crucial for tiller development, especially under dry conditions (Beltagi *et. al.* 2022).

Phosphorus is vital for ATP synthesis, which drives cell division and elongation, promoting lateral shoot (tiller) formation. In phosphorus-deficient conditions, tillering is limited due to restricted root and shoot growth (Wang *et al.* 2010). Adequate phosphorus fertilisation enhances tillering by improving plant vigour and nutrient uptake. AMF promote millet growth by enhancing root development, nutrient absorption and stress tolerance and PSB solubilise insoluble phosphorus, increasing its bioavailability and supporting better root and shoot growth (Gomes *et al.* 2023). The combined action of phosphorus, AMF and PSB resulted

Table 2 Effect of crop residue mulching, phosphorus application rate, PSB and AMF on yield attributes of pearl millet during 2022 and 2023

Treatments	Earhead length (cm)		Earhead girth (cm)		Test weight (g)		Grain yield (t/ha)	
	2022	2023	2022	2023	2022	2023	2022	2023
Crop residue management								
M_1	27.3	28.0	8.08	8.28	7.28	7.36	2.86	2.94
M_2	29.5	30.5	8.43	8.71	7.45	7.51	3.22	3.33
M_3	31.1	32.4	8.81	8.92	7.80	7.87	3.37	3.69
SEM±	0.5	0.6	0.04	0.05	0.06	0.06	0.11	0.13
LSD (p=0.05)	1.9	2.5	0.14	0.21	0.24	0.24	0.43	0.50
Phosphorus management								
S_1	25.6	26.7	7.79	7.97	6.95	7.03	2.84	2.95
S_2	30.4	31.3	8.63	8.98	7.69	7.77	3.23	3.43
S_3	31.3	32.2	8.83	8.99	7.85	7.90	3.32	3.53
S_4	29.8	31.0	8.50	8.60	7.53	7.61	3.20	3.36
SEM±	0.50	0.5	0.03	0.15	0.06	0.04	0.05	0.08
LSD (p=0.05)	1.40	1.5	0.08	0.46	0.19	0.11	0.14	0.25

LSD, Least significant difference. Treatment details are given under Materials and Methods.

in improved growth parameters of pearl millet. Labidi *et al.* (2023) also reported that inoculation with biofertiliser as AMF resulted in higher fresh biomass values than non-inoculated ones, at the stem elongation stage.

Yield attributes and yield: Table 2 indicates that the earhead length of pearl millet was significantly greater under treatment M_3, which was statistically comparable to treatment M_2 in both 2022 and 2023. Specifically, M_3 resulted in a 13.9% and 15.7% increase in earhead length compared to the control in 2022 and 2023, respectively, under crop residue management practices. Regarding phosphorus management, the maximum earhead length was observed with treatment S_3, measuring 31.3 cm in 2022 and 32.2 cm in 2023. This treatment was statistically at par with S_2 and S_4 and significantly outperformed the control (S_1), showing increases of 22.3% and 20.6% in 2022 and 2023, respectively. A trend similar to that of earhead length was observed for earhead girth across both years under crop residue management practices. In the context of phosphorus management, the highest earhead girth during the first year was recorded with treatment S_3 (8.83 cm), followed by S_2 (8.63 cm) and S_4 (8.50 cm). In the second year, treatments S_3, S_2 and S_4 showed statistically comparable results, all of which were significantly superior to the control (S_1).

The treatment M_3 significantly improved earhead length, likely due to better soil moisture and nutrient availability. Phosphorus management, particularly treatment S_3, also led to notable increases in both earhead length and girth. The comparable performance of S_3, S_2 and S_4 highlights the effectiveness of integrated nutrient management with bio-inoculants, supporting their role in sustainably enhancing pearl millet growth. Under crop residue management practices, treatment M_3 resulted in a significantly higher test weight of pearl millet, with increases of 4.81% and 7.14% over M_2 and M_3 in 2022 and 4.79% and 6.92% in 2023, respectively. Treatment M_2 also showed a significant improvement in test weight compared to the control (M_1). Regarding phosphorus management, the highest test weight was observed with treatment S_3, recording 7.85 g in 2022 and 7.90 g in 2023. This treatment was statistically at par with S_2 during both the years of experiment. The lowest test weight was noted in the control treatment S_1, with values of 6.95 g and 7.03 g in 2022 and 2023, respectively.

The findings indicated that crop residue mulching, particularly M_3, positively influenced the test weight of pearl millet, likely by enhancing soil health and nutrient uptake. The consistent increase in test weight under M_3 across both years highlights the role of residue management in improving grain quality. Khairwal *et al.* (2007) reported that incorporation of crop residues has led to a significant improvement in agricultural productivity in the arid region of western Rajasthan. Similarly, phosphorus management through the combined use of 75% RDP + PSB + AMF (S_3) significantly improved test weight, demonstrating the benefits of integrated nutrient strategies (Hussain *et al.* 2021). The comparable performance of S_2 and S_3 suggests that bio-inoculants can effectively supplement reduced phosphorus levels, supporting more efficient and sustainable crop production (Owen *et al.* 2015).

Under crop residue management practices, treatment M_3 resulted in a significantly higher grain yield of pearl millet, showing an increase of 17.8% in 2022 and 25.5%

Table 3 Effect of crop residue mulching, phosphorus application, PSB and AMF on economics of pearl millet during 2022 and 2023

Treatments	Cost of cultivation/ha ($\times10^3$ ₹)		Gross returns/ha ($\times10^3$ ₹)		Net returns/ha ($\times10^3$ ₹)		Net B:C ratio	
	2022	2023	2022	2023	2022	2023	2022	2023
Crop residue management								
M_1	28,317.2	28,842.2	95,744	1,01,075	67,427	72,233	2.38	2.50
M_2	31,083.2	31,608.2	1,02,888	1,06,973	71,804	75,365	2.31	2.38
M_3	32,083.2	32,608.2	1,05,483	1,11,001	73,400	78,393	2.29	2.40
SEM±	-	-	3,207	2,105	3,207	2,105	0.11	0.07
LSD (p=0.05)	-	-	NS	8263	NS	NS	NS	NS
Phosphorus management								
S_1	28,889.6	29,414.6	94,744	99,297	65,854	69,883	2.28	2.38
S_2	31,411.3	31,936.3	1,03,423	1,08,658	72,012	76,721	2.30	2.40
S_3	31,155.6	31,680.6	1,04,425	1,10,729	73,269	79,049	2.35	2.50
S_4	30,521.6	31,046.6	1,02,894	1,06,715	72,372	75,669	2.37	2.44
SEM±	-	-	913	1,256	913	1,256	0.03	0.04
LSD (p=0.05)	-	-	2,713	3,733	2,713	3,733	NS	NS

NS, Non-significant; LSD, Least significant difference; B:C ratio, Benefit-cost ratio. Treatment details are given under Materials and Methods.

in 2023 compared to the control treatment M_1. The yield obtained under M_3 was statistically comparable to that of treatment M_2 in both years, indicating similar effectiveness. Regarding phosphorus management strategies, treatment S_3 significantly enhanced grain yield, with increases of 16.9% in 2022 and 19.7% in 2023 over the control (S_1). The yield response under S_3 was statistically similar to that of treatment S_2 and also comparable to S_4 during both years of the experiment (Table 2), suggesting that these treatments were effective in improving grain yield relative to the control.

Residue mulching on soil moisture conservation, reduced evaporation, improved soil structure and enhanced microbial activity, all of which contribute to better nutrient availability and crop performance under arid conditions (Demo and Bogale 2024). Synergistic effect of chemical and biological inputs, where microbial inoculants such as PSB and AMF likely facilitated improved phosphorus solubilisation and uptake, highlights the potential of integrated nutrient management in promoting sustainable crop production, especially in phosphorus-deficient and resource-constrained arid environment (Adnan *et al.* 2022).

Economics of pearl millet: During both years of the study, the lowest cultivation cost for pearl millet was recorded under M_1 while the highest was associated with M_3. Although M_3 consistently produced higher gross returns than M_1, especially in the second year (where it was statistically at par with M_2), the increased input costs led to no significant differences in net returns among the treatments (Table 3). This suggests that while residue mulching enhances gross income, its effect on net profitability is limited due to higher costs. In phosphorus management, S_3 significantly increased both gross and net returns compared to the control (S_1) in both years. Furthermore, its economic performance was statistically similar to S_2, indicating that integrated phosphorus management with bio-inoculants is a cost-effective and profitable strategy for pearl millet cultivation.

In conclusion, crop residue mulching significantly enhanced the growth, yield attributes and yield of pearl millet compared to non-mulched conditions. Among phosphorus management, 75% RDP combined with PSB and AMF showed superior performance in terms of growth, yield and economic returns. As 100% RDP and 50% RDP + PSB + AMF were statistically comparable, 75% RDP + PSB + AMF is recommended under irrigated conditions, while 50% RDP + PSB + AMF is suitable under limited irrigation condition.

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