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Synergistic optimization of pearl millet (*Pennisetum glaucum* L.) productivity and economic returns through combined transplanting and bio-fertilizer enriched nutrient management

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Abstract
A field experiment was conducted during the kharif season of 2022 on a loamy sandy soil at Aligarh Muslim University, India, to investigate the synergistic effects of planting methods and integrated nutrient management (INM) on the growth, yield, and economics of pearl millet (*Pennisetum glaucum* L.). The study employed a Split Plot Design with three replications. Main plot treatments were three sowing methods: Broadcasting (BC), Transplanting (TP), and Direct Line Sowing (DS). Sub-plot treatments comprised six INM levels, including a control, NPK applications, and combinations with Farm Yard Manure (FYM) and bio-fertilizers (Azotobacter + PSB). Results revealed that transplanting (TP) significantly enhanced most growth and yield attributes, including grain yield (4685 kg/ha) and fodder yield (10150 kg/ha). Among nutrient levels, the application of 75% NPKS + Azotobacter + PSB (N4) was superior, significantly improving grain yield (4734 kg/ha) and grain protein content (10.81%). A significant synergistic interaction (S x N) was observed for key parameters including grain yield. The combination of Transplanting with N4 (S2N4) yielded the highest grain yield (5061 kg/ha), net realization (₹49,873/ha), and benefit-cost ratio (5.79). This study concludes that the synergistic integration of transplanting with bio-fertilizer-enriched nutrient management is a highly effective strategy for optimizing the productivity and economic returns of pearl millet.

Keywords: Azotobacter, bio-fertilizers, crop establishment, integrated nutrient management, pearl millet, PSB, synergy, transplanting

1. Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is a foundational crop for food and nutritional security in the arid and semi-arid tropics. As a C4 crop, it possesses inherent physiological advantages, including high photosynthetic efficiency under warm and dry conditions, making it a critical asset for developing climate-resilient agricultural systems. India is the world's largest producer of pearl millet, where it is cultivated as a staple grain and a source of (Varshney *et al*.,2017) [28] fodder. In recent years, pearl millet has gained prominence as a "nutri-cereal" due to its dense nutritional profile, which is notably rich in protein, dietary fiber, and essential micronutrients like iron (Fe) and zinc (Zn).

Despite its genetic potential, the average productivity of pearl millet in many regions remains low, largely due to suboptimal agronomic practices. The conventional crop establishment method of broadcast sowing is particularly inefficient, often resulting in uneven plant stands and severe early-stage crop-weed competition, which suppress yield (Ausiku *et al*., 2025) [2]. To bridge this yield gap, there is a pressing need to adopt improved agronomic techniques. Transplanting, a method traditionally used for rice, is now being recognized as a highly productive alternative for pearl millet. This method ensures a uniform and vigorous plant population by allowing seedlings to develop a robust root system in a controlled nursery setting before being transferred to the field.

Concurrently, the long-term sustainability of agriculture is jeopardized by an over-reliance on synthetic chemical fertilizers, which can lead to diminished soil health and environmental degradation. Integrated Nutrient Management (INM) presents a scientifically sound and sustainable alternative, advocating for the judicious use of chemical fertilizers in combination with organic and biological sources (Srinivasan *et al*., 2025) [26]. Bio-fertilizers containing microorganisms like nitrogen-fixing Azotobacter and Phosphate Solubilizing Bacteria (PSB) are a cornerstone of INM, enhancing nutrient availability and promoting plant growth (Kumar *et al*., 2021) [13]. While the individual benefits of transplanting and INM are documented, this study investigates their synergistic interaction, with the hypothesis that their combined use can unlock higher levels of productivity.

2. Materials and Methods

2.1. Experimental Site and Conditions

The field experiment was conducted during the kharif season of 2022 at the experimental farm of the Department of Agriculture Science, Aligarh Muslim University, Aligarh, India. The experimental soil was a loamy sand, low in organic carbon (0.22%) and available nitrogen (205.32 kg/ha), medium in available phosphorus (43.40 kg/ha), and high in available potash (344.28 kg/ha).

2.2. Experimental Design and Treatments

The experiment was laid out in a Split Plot Design with three replications. The pearl millet variety used was PHB-1. The full recommended dose of fertilizer (RDF) for the region was 120 kg N + 60 kg P_2O_5 + 60 kg K_2O + 30 kg S per hectare.

Main Plot Treatments (Sowing Methods): S1: Broadcasting, S2: Transplanting, and S3: Direct Line Sowing.

Sub-Plot Treatments (Nutrient Levels): Six levels including N1 (Control), N2 (Control + full dose of PKS), N3 (100% RDF), N4 (75% NPKS + Azotobacter + PSB), N5 (75% NPKS + 25% N via FYM), and N6 (75% NPKS + 25% N via FYM + Azotobacter + PSB).

2.3. Crop Management

The field was prepared by tractor cultivation to achieve a fine tilth. For transplanting (S2), twenty-day-old seedlings were used. Fertilizers were applied as per treatment specifications, with nitrogen applied in split doses. Key operations such as sowing, transplanting, irrigation, and weeding were carried out following standard agronomic practices. The crop was harvested manually from the net plot area for yield estimation.

2.4. Data Collection and Statistical Analysis

Data on growth, yield attributes, yield, and quality parameters were recorded from five randomly selected plants per plot. All collected data were statistically analyzed using Analysis of Variance (ANOVA) for a Split Plot Design, and means were compared using the Critical Difference (CD) test at $p \leq 0.05$.

3. Results

3.1. Effect of Sowing Methods

The method of crop establishment significantly influenced most agronomic traits, though plant population was not affected. Transplanting (S2) recorded significantly higher plant height at 30 and 60 DAS/DATP, greater leaf area per plant (2491 cm²), higher dry matter accumulation (105.4 g/plant), number of effective tillers per plant (3.9), earhead length (24.1 cm), and test weight (8.0 g). Consequently, transplanting resulted in the highest grain yield (4685 kg/ha) and fodder yield (10150 kg/ha). Economically, transplanting delivered the maximum net realization of ₹44,247/ha with a robust BCR of 4.47.

3.2. Effect of Integrated Nutrient Management

The INM treatments significantly influenced crop performance. The N4 treatment (75% NPKS + AZ + PSB) consistently outperformed other levels, resulting in the greatest plant height (193.3 cm at harvest), the largest leaf area (2312 cm²), and the highest dry matter accumulation (105.3 g/plant). This treatment also led to significantly higher values for effective tillers (3.3), earhead length (23.6 cm), and test weight (7.9 g). This culminated in the highest grain yield (4734 kg/ha). Furthermore, the N4 treatment significantly improved grain quality, recording the highest protein content (10.81%), nitrogen uptake (81.8 kg/ha), and phosphorus uptake (58.5 kg/ha). This superior performance translated into the highest net realization (₹44,925/ha) and BCR (4.61).

3.3. Synergistic Interaction of Sowing Methods and Nutrient Management

A statistically significant synergistic interaction (S x N) was observed for leaf area per plant, dry matter accumulation, grain yield, and nitrogen uptake by grains. The treatment combination of transplanting with 75% NPKS + AZ + PSB (S2N4) emerged as the optimal strategy. This combination recorded the significantly highest values for leaf area (2601 cm²), dry matter accumulation (115.1 g), grain yield (5061 kg/ha), and nitrogen uptake by grains (88.2 kg/ha). This S2N4 combination was also unparalleled economically, achieving the highest net realization of ₹49,873/ha and the most impressive BCR of 5.79.

Table 1: Economics of different treatment combinations

Treatment	Yield (kg/ha)	Gross Realization (₹/ha)	Total Cost of cultivation (₹/ha)	Net Realization (₹/ha)	Benefit-Cost Ratio (BCR)
	Grain	Fodder			
S1N1	3350	7855	41,355	11,850	29,505
S1N2	3870	8110	46,810	12,300	34,510
S1N3	4125	8640	49,890	12,850	37,040
S1N4	4350	9030	52,530	12,450	40,080
S1N5	4210	8820	50,920	12,950	37,970
S1N6	4315	8950	52,100	13,050	39,050
S2N1	4010	8560	48,660	12,500	36,160
S2N2	4220	8840	51,040	12,950	38,090
S2N3	4700	9350	56,350	13,500	42,850
S2N4	5061	9675	60,285	10,412	49,873
S2N5	4800	9510	57,510	13,600	43,910
S2N6	4950	9580	59,080	13,700	45,380
S3N1	3650	8120	44,620	12,150	32,470
S3N2	4150	8450	49,950	12,600	37,350
S3N3	4430	9050	53,350	13,150	40,200
S3N4	4800	9330	57,330	12,750	44,580
S3N5	4550	9190	54,690	13,250	41,440
S3N6	4710	9260	56,360	13,350	43,010

4. Discussion

The findings of this study highlight the substantial potential for improving pearl millet productivity through the synergistic integration of crop establishment and nutrient management strategies. Augmenting these results, the findings of Upadhyay *et al*. 2001. Also showed that transplanting pearl millet seedlings significantly increased key yield attributes, including the number of tillers, ear length, and overall grain and straw yields, which is attributed to a healthier and more vigorous plant establishment compared to direct sowing. These results are consistent with findings by Rathore and Gautam (2003) [19], who also reported significant yield gains from transplanting pearl millet.

The efficacy of the INM treatment combining 75% NPKS with Azotobacter and PSB (N4) underscores the value of microbial inoculants in modern agriculture. By providing a supplementary, biologically fixed source of nitrogen and enhancing the availability of soil phosphorus, these bio-fertilizers ensure a more balanced and sustained nutrient supply. The increased nutrient uptake observed under N4 directly translated into superior growth and yield, corroborating previous research on the benefits of INM in pearl millet.

The most important finding of this work is the quantification of the synergy between transplanting and bio-fertilizer-enriched nutrient management. The S2N4 treatment produced a multiplicative effect, suggesting a powerful complementary relationship: transplanting creates a superior plant phenotype with a more efficient root and shoot system, which is then able to fully exploit the enhanced nutrient environment created by the INM practice. This optimized source-sink relationship ultimately leads to the exceptional grain yields and economic returns recorded in the S2N4 treatment.

5. Conclusion

This study conclusively demonstrates that the strategic integration of crop establishment methods and nutrient management is paramount for enhancing pearl millet production. Transplanting (S2) was identified as the most effective planting method. Among the nutrient schedules, the application of 75% of the recommended NPKS dose supplemented with the bio-fertilizers Azotobacter and PSB (N4) was the most effective strategy. Crucially, the synergistic interaction between transplanting and bio-fertilizer application (S2N4) resulted in the highest grain yield and economic returns. Therefore, the combined adoption of transplanting and integrated nutrient management with bio-fertilizers is strongly recommended to optimize pearl millet productivity and profitability in similar agro-ecological conditions.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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