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ORIGINAL ARTICLE

Productivity, Profitability and Grain Mineral Composition of Pearl Millet (*Pennisetum glaucum* L.) under Integrated Nutrient Management and Chelated Micronutrient Sprays

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ABSTRACT
Integrated nutrient management (INM) can raise pearl millet yields, but farmers adopt it only when the extra inputs pay for themselves, and its effect on grain mineral content is rarely measured together with returns. A field experiment was conducted during kharif 2024 and 2025 at Sohna, Haryana, with hybrid MP 7288 and twelve treatments in a randomized block design with three replications. The treatments combined the recommended dose of fertilizers (RDF) with farmyard manure, vermicompost, Azotobacter, phosphate solubilizing bacteria (PSB) and a foliar spray of chelated micronutrients. The treatment 75% RDF + 25% N through vermicompost + Azotobacter + PSB + foliar chelated micronutrients (T11) gave the highest grain yield (29.18 and 30.26 q ha^{-1}), straw yield (52.08 and 53.32 q ha^{-1}), gross returns (₹85,970 and ₹92,763 ha^{-1}) and net returns (₹58,030 and ₹64,554 ha^{-1}) in 2024 and 2025, respectively. The treatment 100% RDF + Azotobacter + PSB + foliar chelated micronutrients (T12) produced statistically similar yields at a cost lower by ₹4,215 to ₹4,341 ha^{-1} and therefore recorded the highest net benefit-cost ratio (2.44 and 2.69). Grain Fe, Zn, Mn, Cu, B, Mo and Ca contents were highest under T11 (Fe 57.26 and 58.72 ppm; Zn 51.42 and 52.76 ppm) and at par with T12. Applied with full RDF, the foliar spray alone raised grain Fe by 8.0 to 8.3 ppm and Zn by 10.4 to 10.7 ppm over RDF without the spray. T12 is the more economical option, while T11 gives the highest absolute returns and grain mineral content.
Keywords: *Agronomic biofortification, Benefit-cost ratio, Grain iron, Grain zinc, Pearl millet, Straw yield*

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INTRODUCTION

Pearl millet (*Pennisetum glaucum* L.) is grown mainly by smallholders in the arid and semi-arid regions of India, who use the grain as food and the stover as dry fodder. Its grain is comparatively rich in protein, iron and zinc, which makes the crop important for nutrition in areas where diets are dominated by cereals [1].

Because pearl millet is usually raised with little capital, any change in nutrient management has to be judged by its returns as well as its yield. Integrated nutrient management (INM), which replaces part of the fertilizer with organic manures and biofertilizers, can sustain yields while improving soil condition. Organic manures, however, add to the cost of cultivation, and their profitability has to be demonstrated for each production system.

Grain mineral content is a second consideration. Zinc and iron deficiencies are common both in Indian soils and in the diets of people who depend on millets. Agronomic biofortification through soil or foliar application of micronutrients can raise their concentration in the grain, and combining it with organic and biological nutrient sources may improve both yield and grain quality [2]. Chelated micronutrients are suited to foliar application because the chelate keeps the metal soluble and allows it to be absorbed through the leaf.

Little information is available on how INM, bio-inoculants and chelated micronutrient sprays together affect the yield, economics and grain mineral composition of pearl millet. This study measured grain and

straw yield, cost and returns, and the grain contents of Fe, Zn, Mn, Cu, B, Mo and Ca under twelve nutrient management treatments.

MATERIAL AND METHODS

Site and soil

The study was carried out during *kharif* 2024 and 2025 at the Crop Research Centre of GD Goenka University, Sohna, Haryana (28.26° N, 77.06° E, 237 m above mean sea level), in the Trans-Gangetic Plains. The sandy loam soil had a pH of 7.58, 0.40% organic carbon, 192.5 kg ha^{-1} available N, 15.4 kg ha^{-1} available P and 248.0 kg ha^{-1} available K, determined by standard methods [3, 4, 5, 6].

Treatments and crop management

Twelve treatments were tested in a randomized block design with three replications on net plots of 4.40 m × 3.50 m: T1, control; T2, 100% RDF (60:30:30 kg $N:P_2O_5:K_2O$ ha^{-1}); T3, 75% RDF + 25% N through FYM; T4, 75% RDF + 25% N through vermicompost; T5, 75% RDF + *Azotobacter* + PSB; T6, 100% RDF + foliar chelated micronutrients (FCM); T7, 75% RDF + 25% N through vermicompost + *Azotobacter* + PSB; T8, 75% RDF + 25% N through FYM + FCM; T9, 75% RDF + 25% N through vermicompost + FCM; T10, 75% RDF + *Azotobacter* + PSB + FCM; T11, 75% RDF + 25% N through vermicompost + *Azotobacter* + PSB + FCM; and T12, 100% RDF + *Azotobacter* + PSB + FCM.

FYM (5 t ha^{-1}) and vermicompost (2 t ha^{-1}) were incorporated before sowing, and *Azotobacter* and PSB were applied as a seed coating. The chelated micronutrient formulation, a commercial product containing Zn-EDTA 3%, Mn-EDTA 1%, Cu-EDTA 1%, Fe organic complex 2.5%, B 0.5% and Mo 0.1%, was sprayed at 1 g L^{-1} of water at 30 DAS, at the late tillering stage before panicle initiation, using a knapsack sprayer. Hybrid MP 7288 was sown at 45 cm × 15 cm on 27 July 2024 and 6 August 2025, and the crop was otherwise managed uniformly.

Yield and grain analysis

Grain and biological yields were recorded from each net plot, and straw yield was obtained by subtracting grain yield from biological yield. Grain samples were oven-dried at 60 °C, ground and digested in a di-acid mixture (HNO_3:$HClO_4$, 9:4). Fe, Zn, Mn, Cu and Ca were determined by atomic absorption spectrophotometry, and B and Mo by AAS. Contents are expressed in ppm on a dry weight basis.

Economic analysis

The cost of cultivation was calculated from the prevailing prices of inputs and operations. Gross returns were obtained by valuing grain at ₹2,500 q^{-1} in 2024 and ₹2,625 q^{-1} in 2025 and straw at ₹250 q^{-1}. Net returns are gross returns minus the cost of cultivation, and the net benefit-cost (B:C) ratio is net returns divided by the cost of cultivation. Return on nutrient investment (RNI) was calculated.

Statistical analysis

Each year was analysed separately by analysis of variance for a randomized block design [7], and treatment means were compared by the critical difference (CD) at P = 0.05.

RESULTS AND DISCUSSION

Grain yield

T11 gave the highest grain yield, 29.18 q ha^{-1} in 2024 and 30.26 q ha^{-1} in 2025 (Table 1), with T12 (27.64 and 28.72 q ha^{-1}) statistically at par. The control yielded 10.84 and 11.26 q ha^{-1}. The three treatments that supplemented fertilizer with both bio-inoculants and the foliar spray (T10, T11 and T12) gave the three highest yields in both years, which suggests that these two inputs contributed more to yield than the choice between FYM and vermicompost. [8] recorded a similar yield response to INM in pearl millet.

Straw yield

Straw yield ranged from 24.98 to 52.08 q ha^{-1} in 2024 and from 25.68 to 53.32 q ha^{-1} in 2025 (Table 1). T11 gave the highest straw yield, with T12 and T10 statistically at par, and exceeded 100% RDF by 49.5% and 49.6% in the two years. The proportional gain in straw was smaller than the gain in grain (about 65%), which is consistent with the slight, non-significant rise in harvest index under the integrated treatments. Pearl millet stover is a major dry fodder in mixed crop-livestock farming, so the extra straw also has cash value; it made up about 15% of the gross returns of T11. [9] also reported higher productivity of pearl millet under INM.

Economics

Cost of cultivation

The cost of cultivation ranged from ₹19,000 ha^{-1} in the control to ₹28,640 and ₹28,929 ha^{-1} under T8 (FYM + foliar spray) in 2024 and 2025 (Table 2). Treatments that included FYM or vermicompost generally cost more than those without organic manure. Bio-inoculants and the foliar spray added

comparatively little: T12 cost only ₹2,538 and ₹2,614 ha^{-1} more than 100% RDF. [10] reported a similar rise in cultivation cost when organic sources were included in pearl millet nutrient schedules.

Gross and net returns

Gross returns followed the yield trend, with T11 highest (₹85,970 and ₹92,763 ha^{-1}), T12 next (₹81,545 and ₹88,120 ha^{-1}) and the control lowest (₹33,345 and ₹35,978 ha^{-1}). Every treatment returned more in 2025, because yields were slightly higher and grain was valued at a higher price. [11] likewise found that better nutrient supply raised the gross returns from pearl millet.

Net returns were also highest under T11 (₹58,030 and ₹64,554 ha^{-1}), but T12 (₹57,820 and ₹64,253 ha^{-1}) trailed by only ₹210 and ₹301 ha^{-1}. The control earned ₹14,345 and ₹16,978 ha^{-1}. T3, which substituted FYM for part of the fertilizer without any other supplement, returned less than 100% RDF in both years (₹21,225 against ₹31,573 ha^{-1} in 2024), so at the yield levels obtained FYM did not recover its own cost. [12] also recorded higher net returns from INM in pearl millet.

Benefit-cost ratio

The net B:C ratio was highest under T12 (2.44 and 2.69), followed by T10 (2.24 and 2.47) and T11 (2.08 and 2.29). The control had the lowest ratio (0.76 and 0.89), and T3 (0.80 and 0.92) was only slightly better. T12 matched T11 in yield at a cost lower by ₹4,215 and ₹4,341 ha^{-1} because it used no vermicompost, and so earned more per rupee invested. The ranking for profitability therefore differs from the ranking for yield, as [13] also observed.

Table 1. Effect of nutrient management treatments on grain, straw and biological yield (q ha^{-1}) of pearl millet

Tr. No.	Treatments	Yield (q ha^{-1})			
		Grain Yield		Straw Yield	
		2024	2025	2024	2025
T1	Control (No fertilizers)	10.84	11.26	24.98	25.68
T2	100% RDF (60:30:30 NPK)	17.62	18.34	34.84	35.64
T3	75% RDF + 25% N through FYM	15.86	16.48	32.86	33.66
T4	75% RDF + 25% N through Vermicompost	18.42	19.18	36.26	37.06
T5	75% RDF + Azotobacter + PSB	19.36	20.12	37.98	38.84
T6	100% RDF + Foliar Spray of Chelated Micronutrients	21.24	22.08	40.94	41.86
T7	75% RDF + 25% N via Vermicompost + Azotobacter + PSB	23.18	24.06	43.64	44.68
T8	75% RDF + 25% N through FYM + Foliar Spray of Chelated Micronutrients	22.14	23.02	42.24	43.20
T9	75% RDF + 25% N through Vermicompost + Foliar Spray of Chelated Micronutrients	24.06	24.98	45.10	46.20
T10	75% RDF + Azotobacter + PSB + Foliar Spray of Chelated Micronutrients	25.62	26.58	47.22	48.38
T11	75% RDF + 25% N via Vermicompost + Azotobacter + PSB + Foliar Spray of Chelated Micronutrients	29.18	30.26	52.08	53.32
T12	100% RDF + Azotobacter + PSB + Foliar Spray of Chelated Micronutrients	27.64	28.72	49.78	50.92
SE(m)±		**0.62**	**0.62**	**1.76**	**2.19**
CD (P=0.05)		**1.83**	**1.80**	**5.16**	**6.43**

RDF, recommended dose of fertilizers (60:30:30 kg N:P_2O_5: K_2O ha^{-1}); FYM, farmyard manure; PSB, phosphate solubilizing bacteria; DAS, days after sowing; CD, critical difference; NS, non-significant.

Return on nutrient investment

RNI was highest under 100% RDF (9.95 and 10.12) and lowest under the FYM treatments T3 (1.60 and 1.73) and T8 (2.26 and 2.34) (Table 2). Mineral fertilizer is cheap relative to the yield response it produces over an unfertilized crop, whereas FYM is costly per unit of nutrient supplied. Among the high-yielding treatments, T10 (7.05 and 7.53) and T12 (6.72 and 7.02) maintained a high RNI, which shows that bio-inoculants and chelated micronutrients are cost-efficient additions to the fertilizer schedule [13].

Grain mineral composition

All seven elements responded significantly to the treatments in both years (Table 3). T11 recorded the highest content of each, statistically at par with T12. Every treatment that received the foliar spray had a higher grain content of every element than every treatment that did not. The specific effect of the spray is clearest in the comparison of T6 with T2, which differ only in the spray: grain Fe rose by 7.98 and 8.28 ppm and Zn by 10.40 and 10.72 ppm, and the increase was significant for all seven elements, including Ca, which the spray did not contain.

Iron and zinc

Grain Fe under T11 was 57.26 and 58.72 ppm, compared with 38.42 and 39.16 ppm in the control, an increase of about 49%; T10 was also at par with T11 for Fe. Grain Zn rose by about 80%, from 28.64 and

29.22 ppm to 51.42 and 52.76 ppm. Zn-EDTA was the largest component of the spray (3%). Chelated Zn and Fe pass readily through the leaf surface and can move to the developing grain, whereas roots absorb both metals poorly from slightly alkaline soils low in organic carbon. Vermicompost and the bio-inoculants probably added to the effect by improving availability in the root zone. [14] and [15] reported similar increases in grain Fe and Zn of pearl millet with agronomic fortification and zinc fertilization.

Manganese and copper

Grain Mn increased from 19.82 and 20.16 ppm in the control to 35.18 and 36.02 ppm under T11, and Cu from 4.12 and 4.24 to 7.12 and 7.42 ppm. Both elements were supplied as EDTA chelates in the spray, and the six treatments without the spray (T1 to T5 and T7) recorded uniformly lower values. [16] also documented higher grain Mn and Cu in pearl millet under improved management.

Table 2. Effect of nutrient management treatments on cost of cultivation, returns and net benefit-cost ratio of pearl millet

Tr. No.	Treatment	Economics									
		Cost of cultivation (₹ ha^{-1})		Gross returns (₹ ha^{-1})		Net returns (₹ ha^{-1})		Net B:C ratio		Return on nutrient investment	
		2024	2025	2024	2025	2024	2025	2024	2025	2024	2025
T1	Control	19,000	19,000	33,345	35,978	14,345	16,978	0.76	0.89	--	--
T2	100% RDF	21,187	21,253	52,760	57,053	31,573	35,800	1.49	1.68	9.95	10.12
T3	75% RDF + 25% N through FYM	26,640	26,869	47,865	51,675	21,225	24,806	0.80	0.92	1.60	1.73
T4	75% RDF + 25% N through Vermicompost	25,140	25,324	55,115	59,613	29,975	34,288	1.19	1.35	6.06	6.74
T5	75% RDF + Azotobacter + PSB	21,987	22,077	57,895	62,525	35,908	40,448	1.63	1.83	6.43	7.04
T6	100% RDF + Foliar Chelated Micronutrients	23,187	23,313	63,335	68,425	40,148	45,112	1.73	1.94	5.22	5.71
T7	75% RDF + Vermicompost + Azotobacter + PSB	25,940	26,148	68,860	74,328	42,920	48,179	1.65	1.84	4.47	4.71
T8	75% RDF + 25% N through FYM + Foliar Chelated Micronutrients	28,640	28,929	65,910	71,228	37,270	42,298	1.30	1.46	2.26	2.34
T9	75% RDF + 25% N through Vermicompost + Foliar Chelated Micronutrients	27,140	27,384	71,425	77,123	44,285	49,738	1.63	1.82	4.55	4.70
T10	75% RDF + Azotobacter + PSB + Foliar Chelated Micronutrients	23,440	23,573	75,855	81,868	52,415	58,294	2.24	2.47	7.05	7.53
T11	75% RDF + Vermicompost + Azotobacter + PSB + Foliar Chelated Micronutrients	27,940	28,208	85,970	92,763	58,030	64,554	2.08	2.29	2.84	2.94
T12	100% RDF + Azotobacter + PSB + Foliar Chelated Micronutrients	23,725	23,867	81,545	88,120	57,820	64,253	2.44	2.69	6.72	7.02

Net B:C ratio = net returns/cost of cultivation. Grain valued at ₹2,500 q^{-1} (2024) and ₹2,625 q^{-1} (2025); straw at ₹250 q^{-1}. RDF, recommended dose of fertilizers (60:30:30 kg N:P_2O_5:K_2O ha^{-1}); FYM, farmyard manure; PSB, phosphate solubilizing bacteria; DAS, days after sowing; CD, critical difference; NS, non-significant.

Table 3. Effect of nutrient management treatments on grain micronutrient and calcium content (ppm) of pearl millet

Tr. No.	Treatment	Grain micronutrient and calcium content (ppm)													
		Fe		Zn		Mn		Cu		B		Mo		Ca	
		2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025
T1	Control	38.42	39.16	28.64	29.22	19.82	20.16	4.12	4.24	3.84	3.96	0.42	0.45	210.6	214.8
T2	100% RDF	41.86	42.74	31.28	32.04	21.64	22.08	4.48	4.62	4.12	4.26	0.48	0.51	224.8	229.2
T3	75% RDF + 25% N through FYM	42.74	43.68	32.46	33.28	22.18	22.64	4.62	4.76	4.26	4.40	0.51	0.54	231.4	236.2
T4	75% RDF + 25% N through Vermicompost	44.18	45.16	34.12	34.98	23.26	23.76	4.86	5.02	4.48	4.64	0.56	0.59	240.8	245.6
T5	75% RDF + Azotobacter + PSB	45.26	46.32	35.46	36.38	24.12	24.66	5.02	5.18	4.62	4.78	0.60	0.63	247.2	252.4
T6	100% RDF + Foliar Chelated Micronutrients	49.84	51.02	41.68	42.76	28.46	29.12	5.74	5.94	5.18	5.36	0.76	0.80	268.4	274.2
T7	75% RDF + Vermicompost + Azotobacter + PSB	47.62	48.74	38.24	39.22	26.18	26.78	5.38	5.56	4.92	5.10	0.68	0.72	258.6	264.2
T8	75% RDF + 25% N through FYM + Foliar Chelated Micronutrients	50.46	51.68	43.12	44.24	29.18	29.86	5.92	6.14	5.36	5.56	0.82	0.86	276.2	282.4
T9	75% RDF + 25% N through Vermicompost + Foliar Chelated Micronutrients	52.18	53.46	45.26	46.44	30.64	31.36	6.18	6.42	5.58	5.80	0.88	0.92	285.8	292.2
T10	75% RDF + Azotobacter + PSB + Foliar Chelated Micronutrients	53.64	54.96	46.84	48.06	31.82	32.58	6.42	6.68	5.76	5.98	0.94	0.98	292.6	299.4
T11	75% RDF + Vermicompost + Azotobacter + PSB + Foliar Chelated Micronutrients	57.26	58.72	51.42	52.76	35.18	36.02	7.12	7.42	6.34	6.60	1.08	1.13	314.8	322.6
T12	100% RDF + Azotobacter + PSB + Foliar Chelated Micronutrients	55.84	57.22	49.36	50.64	33.92	34.74	6.86	7.14	6.12	6.36	1.02	1.07	306.2	313.4
SE(m)±		1.42	1.48	1.18	1.23	0.86	0.90	0.18	0.19	0.16	0.17	0.028	0.030	7.42	7.76
CD (P=0.05)		4.16	4.33	3.46	3.60	2.52	2.64	0.53	0.56	0.47	0.50	0.082	0.088	21.76	22.76

RDF, recommended dose of fertilizers (60:30:30 kg N:P_2O_5:K_2O ha^{-1}); FYM, farmyard manure; PSB, phosphate solubilizing bacteria; DAS, days after sowing; CD, critical difference; NS, non-significant.

Boron and molybdenum

Grain B rose from 3.84 and 3.96 ppm in the control to 6.34 and 6.60 ppm under T11, and Mo from 0.42 and 0.45 to 1.08 and 1.13 ppm, more than double the control value. Boron is required for pollen tube growth and the transport of sugars into the grain [17]. Both elements were present in the spray at low concentrations (0.5% and 0.1%), and these appear to have been enough to raise their grain content

substantially. Grain Mo varies widely among pearl millet genotypes [18], so absolute values should be compared across cultivars with caution.

Calcium

Grain Ca increased from 210.6 and 214.8 ppm in the control to 314.8 and 322.6 ppm under T11. Calcium was not part of the spray, so this response probably reflects better root growth and nutrient uptake by well-nourished plants, with some contribution from Ca in the vermicompost. [18] also reported considerable variation in the grain Ca of pearl millet.

CONCLUSION

T11 gave the highest grain and straw yields, gross and net returns and grain mineral contents in both years. T12, which omits vermicompost, was statistically equal to T11 in yield and grain quality, cost less, and gave the highest net B:C ratio (2.44 and 2.69). For farmers who have to buy organic manure, T12 is the more profitable choice; where vermicompost is produced on the farm, T11 gives the most grain, fodder and grain minerals per hectare.
request.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author on reasonable.

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