

COMPARATIVE EVALUATION OF RDF AND NANO-FERTILIZER COMBINATIONS ON GROWTH AND YIELD OF PEARL MILLET (*Pennisetum glaucum* L.)

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ABSTRACT

Pearl millet (*Pennisetum glaucum* L.) is an important climate-resilient cereal crop, particularly suited to semi-arid environments. Efficient nutrient management is essential for improving its productivity and profitability under such conditions. A field experiment was conducted during the *kharif* seasons of 2023 and 2024 at the Research Farm, Faculty of Agricultural Sciences, Shree Guru Gobind Singh Tricentenary University, Gurugram, Haryana, India, to evaluate the effect of different combinations of recommended dose of fertilizers (RDF) and nano-fertilizers on growth, yield, economics and post-harvest soil nutrient status of pearl millet. The experiment was laid out in a randomized block design with seven treatments and three replications. The treatments comprised 50, 75 and 100% RDF, with or without Nano-DAP seed treatment and foliar application of Nano-Urea and Nano-DAP at different growth stages. The pooled results showed that 75% RDF + Nano-DAP seed treatment @ 10 mL kg⁻¹ seed + three foliar applications of Nano-Urea and Nano-DAP at 15, 25 and 45 DAS (T₇) recorded the highest numerical values for most growth and yield attributes. T₇ recorded the highest plant height (199.44 cm), effective tillers (2.78 plant⁻¹), ear head length (25.49 cm) and grain weight per ear head (19.65 g) test weight (6.08 g). The highest pooled grain yield (2.60 t ha⁻¹), stover yield (6.49 t ha⁻¹) and biological yield (9.08 t ha⁻¹) were also recorded under T₇. T₇ recorded the highest gross returns (₹80,227.50 ha⁻¹) and net returns (₹49,806.96 ha⁻¹), whereas the highest B: C ratio was recorded under T₃ (3.03), followed by T₂ (2.96), T₆ (2.66) and T₇ (2.64). Post-harvest available N, P, K and S were numerically highest under T₇ (188.52, 21.05, 143.13 and 14.66 kg ha⁻¹, respectively), with T₇ being statistically at par with T₆ for several soil nutrient parameters. T₇ was also statistically at par with T₆ for several growth and yield attributes, although T₇ recorded significantly higher stover and biological yields. Overall, the integration of 75% RDF with Nano-DAP seed treatment and foliar application of Nano-Urea and Nano-DAP showed potential for improving pearl millet productivity and absolute economic returns under the irrigated conditions of the study. However, as corresponding 50% and 75% RDF treatments without nano-fertilizers were not included, the independent effect of RDF reduction could not be separated from the effect of nano-fertilizer application.

KEYWORDS: Nano-fertilizers; Nutrient management; Pearl millet; Yield

1. INTRODUCTION

Pearl millet (*Pennisetum glaucum* L.) is known by different names across India; it is commonly called bajra in northern India, sajjalu in Andhra Pradesh and Telangana, bajri in Maharashtra and Gujarat, and kambu in Tamil Nadu (1). Globally, it is the sixth most important cereal crop after rice, wheat, maize, barley, and sorghum. Its importance is largely associated with its nutritional quality and ability to grow under adverse conditions. The grain provides 61.8 g carbohydrates, 10.9 g protein, 5.43 g fat, 11.5 g dietary fibre, and 347 kcal energy per 100g, along with important minerals such as 27.4 mg calcium, 289 mg phosphorus, 124 mg magnesium, 2.7 mg zinc, and 6.4 mg iron per 100 g(2). Its drought tolerance and ability to grow under limited water and low-input conditions make pearl millet particularly important for arid and semi-arid regions of Africa and Asia (2, 3).

Globally, pearl millet is cultivated on approximately 31 million hectares of land area, predominantly in Africa and Asia (1). In India, pearl millet is predominantly cultivated during the rainy (*kharif*) season, with some cultivation during the summer season. In 2023–24, the crop covered 73.75 lakh hectares (7.38 million ha), with a production of 107.16 lakh tonnes (10.72 million tonnes) and an average productivity of 1,453 kg/ha(4). Rajasthan, Maharashtra, Gujarat, Uttar Pradesh, and Haryana together account for approximately 90% of India's total pearl millet production, with Rajasthan alone contributing about 46% (5). The nutritional and agricultural importance of millets has also been recognized through the declaration of 2018 as the “National Year of Millets” by the Government of India and 2023 as the “International Year of Millets” (6).

Efficient nutrient management is essential for achieving higher productivity in pearl millet. Nitrogen (N), phosphorus (P), and potassium (K) are key nutrients influencing crop growth, nutrient uptake, and yield. Recent

field studies have shown that increasing N and P supply can improve plant growth, yield attributes, nutrient uptake, and grain yield of pearl millet (7,8). Integrated application of recommended fertilizers with organic and microbial nutrient sources has been reported to improve the growth and yield of pearl millet compared with the application of inorganic fertilizers alone (9,10). Therefore, balanced and integrated management of N, P, and K, together with appropriate supplementary nutrient sources, is important for improving crop productivity and maintaining soil nutrient availability in pearl millet (10,11).

Nano-fertilizers have gained considerable attention as a potential approach to improving nutrient-use efficiency, enhancing nutrient uptake, and reducing nutrient losses to the environment (12). Nano-NPK has shown potential to maintain crop growth and productivity when used as a supplement to reduced rates of conventional fertilizers, particularly through foliar application (13, 14, 15). Among nano-fertilizer products, nano-urea and nano-DAP are commonly used as sources of nitrogen and nitrogen–phosphorus, respectively, and their appropriate application may improve nutrient uptake and nutrient-use efficiency (16). Their use in combination with conventional fertilizers may provide an opportunity to reduce high analysis fertilizer inputs as well as maintaining crop growth and productivity (13, 16, 14).

Studies on application of nano-fertilizers have demonstrated their potential to improve nutrient use and crop performance; however, limited information is available on their combined application with different levels of conventional fertilizer in pearl millet under field conditions. In particular, the integration of nano-DAP seed treatment with foliar application of nano-urea and nano-DAP under 50%, 75%, and 100% recommended dose of fertilizer (RDF) requires further evaluation. Therefore, the present study was conducted to evaluate these nutrient-management combinations for their effects on the growth and yield of pearl millet and post-harvest soil nutrient status, with the aim of identifying an effective fertilizer strategy for improving crop productivity and economic returns.

2. MATERIALS AND METHODS

2.1 Experimental site and soil characteristics

The field experiment was conducted during the *kharif* seasons of 2023 and 2024 at the Research Farm, Faculty of Agricultural Sciences, Shree Guru Gobind Singh Tricentenary University, Gurugram, Haryana, India. The experimental site is located at approximately 28° N latitude and 77° E longitude, at an elevation of 217 m above mean sea level. The region is characterized by hot and dry climatic conditions, with a pronounced monsoon season during the *kharif* period. Gurugram received approximately 510.5 mm of rainfall during the July–September period in 2023 and 610.5 mm during the corresponding period in 2024, with most precipitation occurring during the southwest monsoon.

Before the start of the experiment in 2023, representative soil samples were collected from the 0–15 cm of soil depth to assess the initial physico-chemical properties, particle-size distribution, and nutrient status of the experimental field. The samples were collected from different locations, composited, air-dried, and processed for analysis. The soil contained 63.55% sand, 18.30% silt, and 18.15% clay and was classified as sandy loam based on Bouyoucos Hydrometer method (17). The soil was alkaline (pH 8.17) in chemical reaction with an electrical conductivity (EC) of 1.38 dS m⁻¹ (21), organic carbon content of 0.43%, determined by the Walkley and Black method (18). Available nitrogen (168.32 kg ha⁻¹) was estimated by the alkaline potassium permanganate method (19), available phosphorus (18.50 kg ha⁻¹) by the Olsen method (20), and available potassium (126.83 kg ha⁻¹) by neutral 1 N ammonium acetate extraction followed by flame photometric determination (21). Available sulphur (S) was 11.85 kg ha⁻¹, determined by the calcium chloride extraction method followed by turbidimetric determination (22). These values represented the initial soil nutrient status for the two-year experiment (2023–2024).

2.2 Experimental design and treatments

The experiment was conducted in a Randomized Block Design (RBD) with seven treatments and three replications, resulting in 21 experimental plots. Each plot measured 7 m × 3 m (21 m²). A 0.5 m wide bund was maintained between adjacent plots, while 0.5 m wide irrigation channels were provided between replications. With seven plots arranged side-by-side in each replication, the total experimental field measured approximately 52 m × 10 m, covering a total area of 520 m², including inter-plot bunds and irrigation channels. The total area occupied by the plots alone was 441 m².

Treatment	Treatment details
T ₁	Control (without RDF)
T ₂	100% recommended dose of fertilizers (RDF)
T ₃	100% RDF + nano-DAP seed treatment at 10 mL kg ⁻¹ seed
T ₄	50% RDF + nano-DAP seed treatment at 10 mL kg ⁻¹ seed + two foliar applications of nano-urea and nano-DAP at 25 and 45 days after sowing (DAS)
T ₅	50% RDF + nano-DAP seed treatment at 10 mL kg ⁻¹ seed + three foliar applications of nano-urea and nano-DAP at 15, 25, and 45 DAS

T₆	75% RDF + nano-DAP seed treatment at 10 mL kg ⁻¹ seed + two foliar applications of nano-urea and nano-DAP at 25 and 45 DAS
T₇	75% RDF + nano-DAP seed treatment at 10 mL kg ⁻¹ seed + three foliar applications of nano-urea and nano-DAP at 15, 25, and 45 DAS

2.3 Crop establishment and nutrient management

Pearl millet (*Pennisetum glaucum* L.) was grown at a spacing of 45 cm × 15 cm using Pioneer Hybrid Bajra 86 M90. The crop was sown on 12 July in both 2023 and 2024, with a seed rate of 4 kg ha⁻¹. The recommended dose of fertilizer (RDF) was 80 kg N, 40 kg P₂O₅ and 40 kg K₂O ha⁻¹, supplied through urea, diammonium phosphate (DAP) and muriate of potash (MOP), respectively. Accordingly, the 100% RDF treatment supplied 80-40-40 kg N-P₂O₅-K₂O ha⁻¹, whereas the 75% and 50% RDF treatments supplied 60-30-30 and 40-20-20 kg N-P₂O₅-K₂O ha⁻¹, respectively. The full doses of P₂O₅ and K₂O and half of the recommended N were applied basally at sowing, while the remaining half of N was top-dressed at 30 days after sowing (DAS). IFFCO Nano-Urea and Nano-DAP were used as nano-fertilizer sources. Nano-Urea contained 4% total N (w/v), whereas Nano-DAP contained 8% total N and 16% P₂O₅ (w/v), according to the manufacturer's specifications. Nano-DAP was applied as a seed treatment at 10mL kg⁻¹ seed in the treatment combination from T₃ to T₇ with a seed rate of 4 kg ha⁻¹, this corresponded to 40 mL Nano-DAP ha⁻¹.

In treatments T₄ and T₆, Nano-Urea and Nano-DAP were applied as foliar sprays at 4 mL L⁻¹ each at 25 and 45 DAS, using spray volumes of 400 and 500 L ha⁻¹, respectively. Accordingly, 1.60 and 2.00 L ha⁻¹ of each nano-fertilizer were applied during the first and second sprays, respectively, giving a cumulative application of 3.60 L ha⁻¹ each of Nano-Urea and Nano-DAP. Based on the declared nutrient concentrations, the two sprays supplied approximately 0.144 kg N ha⁻¹ from Nano-Urea, 0.288 kg N ha⁻¹ from Nano-DAP and 0.576 kg P₂O₅ ha⁻¹ from Nano-DAP.

In treatments T₅ and T₇, Nano-Urea and Nano-DAP were applied as foliar sprays at 4 mL L⁻¹ each at 15, 25 and 45 DAS, using spray volumes of 350, 400 and 500 L ha⁻¹, respectively. Thus, 1.40, 1.60 and 2.00 L ha⁻¹ of each nano-fertilizer were applied at the three spray timings, resulting in a cumulative application of 5.00 L ha⁻¹ each of Nano-Urea and Nano-DAP. Based on the declared nutrient concentrations, these three sprays supplied approximately 0.200 kg N ha⁻¹ from Nano-Urea, 0.400 kg N ha⁻¹ from Nano-DAP and 0.800 kg P₂O₅ ha⁻¹ from Nano-DAP. All other agronomic practices, including irrigation, weed management and plant-protection measures, were maintained uniformly across treatments during both the 2023 and 2024 *kharif* seasons.

2.4 Observations recorded

Growth and yield attributes were recorded from five randomly selected plants in each plot. Plant height was measured from the soil surface to the tip of the panicle, and the number of effective tillers per plant was recorded at maturity. Yield attributes, including ear head length, grain weight per ear head and test weight, were recorded at maturity. The crop from each net plot was harvested separately to determine grain and stover yields, which were subsequently converted to a hectare basis. Biological yield was calculated as the sum of grain and stover yields, while the harvest index was calculated as the percentage of grain yield relative to biological yield.

2.5 Economics of cultivation

The economics of different treatments were evaluated based on the prevailing prices of inputs and produce during the respective experimental seasons. The cost of cultivation was calculated by considering the expenditure incurred on various cultivation operations and inputs. Gross returns were estimated from the market value of grain and stover yields, while net returns were calculated by subtracting the cost of cultivation from the gross returns. The benefit: cost ratio was determined as the ratio of gross returns to the total cost of cultivation.

2.6 Post-harvest soil analysis

After harvest during each experimental season, soil samples were collected separately from each experimental plot at a depth of 0-15 cm to assess changes in soil nutrient status resulting from the different treatments. The samples were air-dried, processed, and analysed for available nitrogen, phosphorus, potassium, and sulphur. Available N, P, K and S were determined using the same procedures described for the initial soil analysis. Available sulphur was estimated by the calcium chloride extraction method followed by turbidimetric determination.

2.7 Statistical analysis

Data recorded during the *kharif* seasons of 2023 and 2024 were subjected to analysis of variance appropriate for a randomized block design. The data were initially analysed separately for each year to assess treatment effects within individual seasons. Subsequently, pooled analysis over the two years was performed. The Year × Treatment interaction was tested to determine whether treatment responses differed significantly between the two experimental years. When the Year × Treatment interaction was non-significant, treatment means were pooled across the two years and used for interpretation. Pooled treatment means were compared using the critical difference (C.D.) test at the 5% probability level ($P = 0.05$). Statistical analyses were performed using OPSTAT software.

3. RESULTS AND DISCUSSION

3.1 Growth Attributes

3.1.1 Plant height

Plant height increased progressively from 30 DAS to harvest across all treatments. At 30 DAS, plant height ranged from 43.72 cm in T₁ to 67.80 cm in T₃. Treatment T₃ recorded the maximum plant height (67.80 cm) and was statistically at par with T₇ (67.15 cm), T₆ (65.05 cm) and T₂ (64.48 cm), whereas T₁ recorded the minimum value. At 60 DAS, the maximum plant height was recorded in T₃ (143.94 cm), which remained statistically at par with T₇ (136.59 cm) and T₂ (133.49 cm), while T₆ (129.83 cm) recorded a significantly lower plant height than T₃. The minimum plant height was observed in T₁ (75.44 cm). At harvest, T₇ recorded the highest plant height (199.44 cm), followed by T₆ (192.90 cm) and T₃ (188.23 cm), whereas T₁ recorded the lowest plant height (94.64 cm). The CD (P = 0.05) values were 6.41, 13.32, and 18.13 cm at 30 DAS, 60 DAS, and harvest, respectively, indicating significant differences among the nutrient-management treatments.

The superior plant height recorded under T₇ (75% RDF + nano-DAP seed treatment + three nano-sprays) may be attributed to improved nutrient availability and utilization resulting from the integration of soil-applied fertilizers with nano-fertilization. Foliar application of nano-urea with different levels of conventional nutrients has been reported to influence growth and agronomic performance of pearl millet under rainfed conditions (23). Similarly, application of nano-fertilizers has been reported to improve agronomic traits of pearl millet under irrigated conditions (24), while foliar application of nano-urea has also been reported to influence growth and yield of summer pearl millet (25). These findings provide direct support for the beneficial association between nano-fertilizer-based nutrient management and improved growth of pearl millet.

The favourable response of T₇ may also be related to improved N and P nutrition. Increasing levels of nitrogen and phosphorus have been reported to significantly improve plant height, leaf number, SPAD value and dry weight in pearl millet (7). Therefore, the greater plant height observed under T₇ may be associated with improved nutrient supply and utilization, which supported vegetative growth and biomass accumulation. The positive response of pearl millet to integrated soil and foliar nutrient application has also been reported under field conditions (26). The lower plant height recorded under the control treatment further indicates the importance of adequate nutrient availability for optimum crop growth.

3.1.2 Effective Tillers Plant⁻¹

The number of effective tillers plant⁻¹ ranged from 1.78 in T₁ to 2.78 in T₇. Treatment T₇ recorded the highest number of effective tillers (2.78), followed by T₆ (2.70) and T₃ (2.51). Treatments T₄ (2.39) and T₅ (2.44) showed intermediate values, whereas T₂ (2.34) and T₁ (1.78) recorded comparatively lower values. The CD value was 0.25, indicating significant differences among the nutrient-management treatments.

The higher number of effective tillers recorded under T₇ may be associated with improved crop nutritional status resulting from the combined application of RDF and nano-fertilizers. In pearl millet, foliar application of nano-urea with different levels of nutrients has been reported to influence agronomic performance (23), while nano-fertilizer application has also been reported to affect agronomic traits under irrigated conditions (24). Foliar application of nano-urea has similarly been evaluated for its effects on growth and yield of summer pearl millet (25). These findings support the potential role of nano-fertilizer supplementation in improving growth-related characteristics of pearl millet.

Table1. Two year (2023-2024) Pooled data effect of nutrient management treatments on growth and yield attributes of pearl millet

Treatments	Plant Height (cm)			Effective tillers plant ⁻¹	Ear head length (cm)	Grain weight ear head ⁻¹ (g)	Test weight (g)
	30 DAS	60 DAS	At Harvest				
T ₁	43.72	75.44	94.64	1.78	19.58	14.68	5.44
T ₂	64.48	133.49	185.50	2.34	23.46	17.68	5.64
T ₃	67.80	143.94	188.23	2.51	23.83	18.38	5.84
T ₄	54.20	123.07	153.76	2.39	23.04	17.10	5.64

T₅	56.30	126.39	157.18	2.44	23.76	17.41	5.70
T₆	65.05	129.83	192.90	2.70	24.78	18.95	5.91
T₇	67.15	136.59	199.44	2.78	25.49	19.65	6.08
S.E.(m) ±	2.08	4.32	5.89	0.08	0.77	0.59	0.10
C.D. (P = 0.05)	6.41	13.32	18.13	0.25	2.38	1.82	0.33

Note: Values are pooled means of 2023 and 2024. S.E. (m) ± = standard error of mean; C.D. (P = 0.05) = critical difference at the 5% level.

The higher tillering under T₇ may further be related to improved nutrient availability under integrated nutrient management. Balanced nitrogen and phosphorus nutrition has been shown to improve growth and yield-related characteristics of pearl millet (7). Thus, the greater number of effective tillers observed under T₇ may be associated with improved nutritional conditions and better vegetative development. The comparatively lower tiller number under the control treatment may be attributed to inadequate nutrient availability, which restricted overall crop growth and productive tiller development.

3.2 Yield Attributes

3.2.1 Ear Head Length

Ear head length varied from 19.58 cm (T₁) to 25.49 cm (T₇). The maximum ear head length was recorded under T₇ (25.49 cm), which was statistically at par with T₆ (24.78 cm), T₃ (23.83 cm) and T₅ (23.76 cm). T₄ (23.04 cm) and T₂ (23.46 cm) recorded comparatively lower values. Longer ear heads under T₇ may be attributed to the improved nutritional status of the crop resulting from the combined application of RDF and nano-fertilizers.

Table 2. Two year (2023-2024) Pooled data effect of nutrient management treatments on yield, yield attributes and economics of pearl millet

Treatments	Grain yield (t ha ⁻¹)	Stover yield (t ha ⁻¹)	Biological yield (t ha ⁻¹)	Harvest index (%)	Cost of cultivation (₹ ha ⁻¹)	Gross returns (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	Benefit: cost ratio
T₁	1.37	2.74	4.11	33.33	18000.00	39045.00	21045.00	2.17
T₂	2.34	5.25	7.59	30.80	23481.07	69397.50	45916.43	2.96
T₃	2.40	5.39	7.78	30.81	23529.07	71202.50	47673.43	3.03
T₄	2.28	4.90	7.18	31.76	26759.14	66595.00	39835.86	2.49
T₅	2.33	5.01	7.34	31.77	29069.14	68067.50	38998.36	2.34
T₆	2.50	5.75	8.24	30.31	28110.54	74812.50	46701.96	2.66
T₇	2.60	6.49	9.08	28.59	30420.54	80227.50	49806.96	2.64
S.E.(m) ±	0.08	0.17	0.25	1.00	—	—	—	—

C.D. (P = 0.05)	0.24	0.54	0.77	3.08	–	–	–	–
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Note: Values are pooled means of 2023 and 2024. S.E. (m) $\pm$ = standard error of mean; C.D. (P = 0.05) = critical difference at the 5% level.

Improved nutrient availability during reproductive growth may have favoured ear head development (25, 28).

3.2.2 Grain Weight Ear Head⁻¹

Grain weight per ear head ranged from 14.68 g in T₁ to 19.65 g in T₇. Treatment T₇ recorded the maximum grain weight per ear head (19.65 g), which was statistically at par with T₆ (18.95 g) and T₃ (18.38 g), but significantly higher than T₅ (17.41 g). T₄ (17.10 g) and T₂ (17.68 g) recorded comparatively lower values. Higher grain weight under T₇ may be attributed to better grain development and filling resulting from improved nutrient availability under integrated nutrient management. Similar improvement in grain weight per ear was reported with nano-fertilizer-based nutrient management in pearl millet (27,28).

3.2.3 Test Weight (1000-Grain Weight)

Test weight ranged from 5.44 g in T₁ to 6.08 g in T₇. Based on the C.D. value of 0.33 g, T₇ was statistically at par with T₆ (5.91 g), T₃ (5.84 g), whereas it recorded significantly higher test weight than T₅ (5.70 g), T₂ (5.64 g), T₄ (5.64 g) and T₁ (5.44 g). The higher test weight under the integrated nutrient-management treatments may indicate improved grain filling and development under better nutrient availability (27, 28, 29).

3.3 Yield and Biomass Production

3.3.1 Grain Yield

Grain yield ranged from 1.37 t ha⁻¹ (T₁) to 2.60 t ha⁻¹ (T₇). T₇ recorded the maximum grain yield (2.60 t ha⁻¹) and was statistically at par with T₆ (2.50 t ha⁻¹) and T₃ (2.40 t ha⁻¹), while it was significantly superior to T₂ (2.34 t ha⁻¹). T₄ (2.28 t ha⁻¹) and T₅ (2.33 t ha⁻¹) recorded comparatively lower yields. The control treatment (T₁) produced the lowest grain yield (1.37 t ha⁻¹). Substantial yield increase under T₇ may be attributed to the cumulative improvement in growth and yield attributes under integrated nutrient management. Integration of 75% RDF with nano-fertilizers may have improved nutrient availability through soil and foliar application, thereby supporting tillering, ear head development and grain formation. Similar improvement in grain yield of pearl millet with reduced conventional nitrogen supplemented with foliar nano-urea has been reported (25, 28). Positive responses of pearl millet to N-nano fertilizer and foliar nano-nitrogen have also been reported (27, 29). The lower yield under reduced RDF treatments indicates the importance of adequate basal nutrient supply for achieving higher productivity.

3.3.2 Stover Yield

Stover yield ranged from 2.74 t ha⁻¹ (T₁) to 6.49 t ha⁻¹ (T₇). T₇ recorded the maximum stover yield (6.49 t ha⁻¹), significantly higher than T₆ (5.75 t ha⁻¹), T₃ (5.39 t ha⁻¹), and T₂ (5.25 t ha⁻¹). T₄ (4.90 t ha⁻¹) and T₅ (5.01 t ha⁻¹) showed intermediate values. Higher stover yield under T₇ may be associated with improved vegetative growth and dry matter accumulation resulting from better nutrient availability. Similar increases in stover or fodder yield under improved nutrient management and nano-fertilizer application have been reported in pearl millet (25, 28, 29). The higher stover production under T₇ was accompanied by higher grain yield, indicating an overall improvement in crop biomass production under integrated nutrient management.

3.3.3 Biological Yield

Biological yield (grain + stover) ranged from 4.11 t ha⁻¹ (T₁) to 9.08 t ha⁻¹ (T₇). T₇ recorded the maximum biological yield (9.08 t ha⁻¹), significantly higher than T₆ (8.24 t ha⁻¹), T₃ (7.78 t ha⁻¹), and T₂ (7.59 t ha⁻¹). T₄ (7.18 t ha⁻¹) and T₅ (7.34 t ha⁻¹) showed intermediate values. Maximum biological yield under T₇ indicates greater total dry matter production resulting from improved growth and yield performance. Similar improvement in growth, yield attributes and overall productivity under improved nutrient management and combined soil and foliar nutrient application has been reported in pearl millet (26, 28). The lower biological yield under 50% RDF treatments further indicates the importance of adequate nutrient supply for maximizing total biomass production.

Table 3. Two year (2023-2024) Pooled data effect of nutrient management treatments on post-harvest soil available nutrient status under pearl millet

Treatments	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Available S (kg ha ⁻¹)
T ₁	166.96	18.43	125.73	11.78
T ₂	173.56	19.20	133.25	12.80

T₃	178.62	19.55	137.48	13.15
T₄	181.60	19.96	138.32	13.54
T₅	184.10	20.34	139.94	13.94
T₆	187.04	20.59	141.51	14.27
T₇	188.52	21.05	143.13	14.66
S.E.(m) ±	3.23	0.39	2.96	0.46
C.D. (P = 0.05)	9.95	1.21	9.13	1.42

Note: Values are pooled means of 2023 and 2024. S.E. (m) ± = standard error of mean; C.D. (P = 0.05) = critical difference at the 5% level.

3.4 Harvest Index

Harvest index ranged from 28.59% (T₇) to 33.33% (T₁). The highest harvest index was recorded under the control treatment (T₁: 33.33%), followed by T₂ (30.80%), T₃ (30.81%), T₄ (31.76%), and T₅ (31.77%). The lowest harvest index was observed under T₇ (28.59%) and T₆ (30.31%). The higher harvest index under T₁ indicates a greater proportion of total biomass was represented by grain, whereas the lower values under the higher-yielding treatments suggest greater accumulation of stover biomass relative to grain. Similar variation in harvest index with fertilizer and nutrient-management treatments has been reported in pearl millet (26, 28). The lower harvest index under T₇, despite its higher grain yield, may therefore be associated with the substantially greater stover production observed under this treatment. Similar responses, where nutrient management increased both grain and stover production, have been reported in pearl millet (26, 27).

3.5 Economics of Nutrient Management

Cost of cultivation ranged from ₹18,000.00 ha⁻¹ in T₁ to ₹30,420.54 ha⁻¹ in T₇, while gross returns ranged from ₹39,045.00 to ₹80,227.50 ha⁻¹, respectively. The highest net returns were recorded under T₇ (₹49,806.96 ha⁻¹), followed by T₃ (₹47,673.43 ha⁻¹) and T₆ (₹46,701.96 ha⁻¹). In contrast, the highest B:C ratio was recorded under T₃ (3.03), followed by T₂ (2.96), T₆ (2.66), T₇ (2.64), T₄ (2.49), T₅ (2.34) and T₁ (2.17). The higher gross and net returns under T₇ were associated with its highest grain yield and stover yield; however, its higher expenditure on nano-fertilizers and three foliar applications reduced the B:C ratio compared with T₃ and T₆. T₆ recorded a slightly higher B:C ratio (2.66) than T₇ (2.64), indicating that the additional spray in T₇ increased production and absolute returns but did not proportionately increase returns relative to input cost. The 50% RDF-based treatments T₄ and T₅ recorded lower B:C ratios (2.49 and 2.34), whereas the control T₁ recorded the lowest net return (₹21,045.00 ha⁻¹) and B:C ratio (2.17). Overall, T₇ gave the maximum gross and net returns, whereas T₃ provided the highest return relative to the cost of cultivation, demonstrating the importance of balancing yield enhancement with fertilizer and nano-fertilizer expenditure (25,27,29).

3.6 Post-Harvest Soil Available Nutrients

3.6.1 Available Nitrogen

Post-harvest soil sample analysis showed available N ranged from 166.96 kg ha⁻¹ (T₁) to 188.52 kg ha⁻¹ (T₇). The maximum available N was recorded under T₇ (188.52 kg ha⁻¹), followed by T₆ (187.04 kg ha⁻¹), T₅ (184.10 kg ha⁻¹), T₄ (181.60 kg ha⁻¹), T₃ (178.62 kg ha⁻¹), and T₂ (173.56 kg ha⁻¹). Based on the C.D. value of 9.95 kg ha⁻¹, T₇ recorded significantly higher available N than T₁ and T₂, whereas it was statistically at par with T₃, T₄, T₅ and T₆. The higher post-harvest available N under T₇ compared with T₂ may be attributed to the greater nutrient input under the integrated nutrient management treatment and the contribution of foliar nitrogen application. Similar differences in post-harvest soil available N under different nutrient-management practices have been reported in pearl millet (25, 27). The lowest available N under the control treatment indicated greater net removal of nitrogen by the crop in the absence of external nutrient supplementation.

3.6.2 Available Phosphorus

Available P ranged from 18.43 kg ha⁻¹ (T₁) to 21.05 kg ha⁻¹ (T₇). The maximum available P was recorded under T₇ (21.05 kg ha⁻¹), followed by T₆ (20.59 kg ha⁻¹), T₅ (20.34 kg ha⁻¹), T₄ (19.96 kg ha⁻¹), T₃ (19.55 kg ha⁻¹), and T₂ (19.20 kg ha⁻¹). Based on the C.D. value of 1.21 kg ha⁻¹, T₇ recorded significantly higher available P than T₁, T₂ and T₃, whereas it was statistically at par with T₄, T₅ and T₆. The higher available P under T₇ compared with T₂ may be associated with the greater P input through the integrated nutrient management treatment, including nano-DAP application. Improvement in post-harvest available P under nutrient-management treatments has also been reported in millet-based cropping systems (25, 27). The lower available P under the control treatment may be related to greater crop removal of phosphorus without adequate external replenishment.

3.6.3 Available Potassium

Available K ranged from 125.73 kg ha⁻¹ (T₁) to 143.13 kg ha⁻¹ (T₇). The maximum available K was recorded under T₇ (143.13 kg ha⁻¹), followed by T₆ (141.51 kg ha⁻¹), T₅ (139.94 kg ha⁻¹), T₄ (138.32 kg ha⁻¹), T₃ (137.48 kg ha⁻¹), and T₂ (133.25 kg ha⁻¹). Based on the C.D. value of 9.13 kg ha⁻¹, T₇ recorded significantly higher available K than T₁ and T₂, whereas it was statistically at par with T₃, T₄, T₅ and T₆. Despite potassium not being applied through foliar sprays, T₇ recorded the highest available K (143.13 kg ha⁻¹) compared with T₂ (133.25 kg ha⁻¹). This may be associated with the overall improvement in crop growth and nutrient management under T₇, which could have influenced nutrient uptake and the balance of potassium in the soil. Similar variation in post-harvest available K under different nutrient-management practices has been reported in pearl millet (25, 27). The lowest available K under the control treatment suggests comparatively greater net removal of potassium by the crop.

3.6.4 Available Sulfur

Available S ranged from 11.78 kg ha⁻¹ (T₁) to 14.66 kg ha⁻¹ (T₇). The maximum available S was recorded under T₇ (14.66 kg ha⁻¹), followed by T₆ (14.27 kg ha⁻¹), T₅ (13.94 kg ha⁻¹), T₄ (13.54 kg ha⁻¹), T₃ (13.15 kg ha⁻¹), and T₂ (12.80 kg ha⁻¹). Based on the C.D. value of 1.42 kg ha⁻¹, T₇ recorded significantly higher available S than T₁, T₂ and T₃, whereas it was statistically at par with T₄, T₅ and T₆. The higher available S under T₇ compared with T₂ may be associated with differences in nutrient management and the resulting changes in crop nutrient uptake and soil nutrient balance. The lower available S under the control treatment indicates greater net nutrient removal in the absence of additional nutrient inputs. Differences in post-harvest soil nutrient status under nutrient-management practices have been reported in pearl millet (26).

4. CONCLUSION

The study demonstrated that the integrated application of 75% recommended dose of fertilizers (RDF) with Nano-DAP seed treatment and three foliar applications of Nano-Urea and Nano-DAP at 15, 25 and 45 DAS (T₇) recorded the highest numerical values for growth, yield attributes and yield of pearl millet. The treatment combination T₇ recorded the highest plant height (199.44 cm), effective tillers (2.78 plant⁻¹), ear head length (25.49 cm), grain weight per ear head (19.65 g), test weight (2.65 g), grain yield (2.60 t ha⁻¹), stover yield (6.49 t ha⁻¹) and biological yield (9.09 t ha⁻¹). Treatment combination T₇ was statistically at par with treatment combination T₆ for most growth and yield attributes, while significant superiority of T₇ over T₆ was observed for stover and biological yields. T₇ produced 89.8% higher grain yield than the control and recorded the highest gross returns (₹80,227.50 ha⁻¹) and net returns (₹49,806.96 ha⁻¹). However, the highest Benefit-Cost ratio (B:C) was recorded under T₃ (3.03), followed by T₂ (2.96), T₆ (2.66) and T₇ (2.64). The lower B:C ratio under T₇ (2.64) compared to T₃ (3.03) reflects the relatively higher market cost of nano-fertilizers and the need for three foliar sprays, which raises the cost of cultivation. However, this narrow margin in economic efficiency should not overshadow the substantial agronomic and environmental advantages of nano-fertilizer integration. T₇ produced the highest grain, stover and biological yields, along with the highest gross and net returns. Beyond yield, nano-fertilizers enhance nutrient-use efficiency through targeted delivery, reduce fertilizer losses via volatilization and leaching, and support sustainable soil health, as evidenced by higher post-harvest available N, P, K and S. Thus, although the B:C ratio is marginally lower, the integrated nano-fertilizer package offers superior productivity, profitability and ecological sustainability, making it a viable option for precision nutrient management in pearl millet. Post-harvest soil analysis also recorded the highest numerical values of available N, P, K and S under T₇, although T₇ was statistically at par with T₆ for these parameters. Overall, T₇ resulted in the highest crop productivity and absolute economic returns, whereas T₃ provided the highest return relative to the cost of cultivation. The results indicate that the integrated 75% RDF + nano-fertilizer package has potential for improving pearl millet productivity under the irrigated conditions of the present study. However, because corresponding 50% and 75% RDF treatments without nano-fertilizers were not included, the independent effect of RDF reduction could not be separated from the effect of nano-fertilizer application; therefore, the results should be interpreted as the performance of the integrated nutrient-management package rather than definitive evidence of a standalone 25% RDF reduction.

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