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RESEARCH ARTICLE

Influence of nano fertilizers on agronomic traits of pearl millet (*Pennisetum glaucum* L.) under irrigated conditions

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Abstract

Pearl millet is a nutrient-dense cereal grain that can withstand heat and drought. The study aimed to assess the impact of nano fertilizers, combining inorganic and organic sources, on pearl millet's growth and yield parameters. Two season field trials were conducted in the south farm of Karunya University, Coimbatore (10.934°N Latitude, 76.75°E Longitude) during the late *kharif* season of 2022 and 2023. The field experiment was conducted in Factorial Randomized Block Design (FRBD) with 2 factors, soil and foliar applications. The treatments included soil treatments with 100% Recommended dose of fertilizer (RDF), 75% RDF + Farmyard manure (FYM), 75% RDF + Vermicompost, 50% RDF + FYM and 50% RDF + Vermicompost, as well as foliar treatments with Nano DAP, Nano urea and Nanoemulsion biofertilizer. The Nanoemulsion biofertilizer treatment at 30 and 45 days after sowing (DAS) (F3) increased plant height (198.85 cm), no. of tillers/plant (6.10), dry matter production (7093.46 kg/ha), leaf area index (LAI) (1.66), chlorophyll index (32.36), crop growth rate (CGR) (6.43 g/m/day), ear head length (24.34 cm), ear head girth (3.41 cm), total number of effective tillers/plant (5.33) and test weight (14.44 g) were all higher for the 50% RDF + Vermicompost at 5 t/ha treatment than for the other soil and foliar spray treatments. Integrated nutrient management with nanoemulsion biofertilizer application was chosen as a better option to increase higher crop yield improvements by 10-30%, potentially reducing chemical fertilizer costs by 20-40% and enhancing farmers' profit margins by 15 - 50%. By integrating this approach, large-scale agricultural operations could see significant financial benefits, making it an attractive option for commercial adoption.

Keywords: Karunya University; nano DAP; nanoemulsion; pearl millet; yield

Introduction

Pearl millet, the fourth most significant cereal crop, is heat and drought-tolerant and can thrive on low-fertilized soil. Pearl millet, a sixth-ranked crop globally, contributes 42% of total world production after rice, wheat, maize, barley and sorghum (1). This food source serves over 90 million people globally and is a common staple in Africa and Northwest India (2). In India, pearl millet is produced on 7.38 million ha with an average yield of 10.72 million tonnes and a productivity of 1453 kg/ha (3). The soil becomes nutrient-deficient, unable to naturally renew nutrients, rendering it unusable and unfertile (4). Balanced nutrient management is crucial for maintaining soil fertility and enhancing output. Due to the high cost of chemical fertilizers and their detrimental effects on soil health, organic nutrition management and mixing chemical and organic sources are growing in popularity (5).

The idea behind Integrated Nutrient Management (INM) aims to enhance soil productivity over time by utilizing organic manures, fertilizers and biofertilizers in appropriate amounts for different crops and agroecological conditions. The improved physical characteristics of the soil and the availability of nutrients to plants may be the cause of the increased yield seen when Vermicompost and chemical fertilizer are combined. Organic manure provides a conducive environment for microorganisms like *Azospirillum* and phosphate-solubilizing bacteria, which stabilize atmospheric nitrogen and phosphorus available to plants (6).

By using certain nano-material coatings to break down organic fertilizer to a nanoscale (1 - 100 nm), nano-biofertilizer - a blend of nanoparticles and biofertilizers-is created. Nano-biofertilizer offers sustainable, slow and regulated delivery of essential nutrients to plants, providing gradual availability over a long period (7). The approach includes enclosing biofertilizers in nanomaterials to alleviate environmental stresses and manage nutrient distribution within the soil. Practices that enhance nutrients boost their availability and absorption, lower the need for chemical fertilizers, are economical and are beneficial for the environment (8). Nano and biofertilizers have become increasingly favored in the agricultural sector as excellent alternatives, experiencing a surge in acceptance and interest (9, 10).

However, in agriculture, nano-fertilizers are essential for improving growth and output, reducing fertilizer waste, increasing nutrient use efficiency and lowering cultivation expenses, among other things. Current agricultural issues, especially those pertaining to iron and zinc inadequacies in the human population, may be effectively resolved with the use of such resources.

Nanoparticles impact nutrient accessibility in plant-microbe interactions, indirectly affecting bacterial strains (11). Nano-biofertilizers, a blend of nanoparticles and biofertilizers, improve fertilizer benefits, crop productivity and soil microbial conditions (12). Nano-biofertilizers, with their nitrogen fixation, phosphate solubility, and hormone-boosting properties, contribute to improved soil microbial conditions and plant growth by promoting urea and microorganisms (13). They enhance nutrient absorption, diffusion, and slow release, promoting sustainable plant growth (14). Nano biofertilizers are innovative agricultural products that improve plant nutrient uptake and soil health, and promote sustainable farming practices. This technology enhances agricultural operations and food production (15). Nanoemulsions (NE) have a more cost-effective production process and a simpler formulation.

To establish a sustainable crop production system, integrating precision nutrient management with advanced biofertilizer technologies is crucial. The latest approach involves combining chemical fertilizers with organic alternatives like Vermicompost and foliar application of nanoemulsion biofertilizers enriched with beneficial microbes such as *Azospirillum* and phosphate-solubilizing bacteria (PSB). This strategy enhances nutrient uptake efficiency, promotes soil health, and ensures higher productivity. The current study focuses on optimizing nanoemulsion biofertilizer applications while reducing chemical fertilizer dependency, aligning with modern agricultural trends in regenerative and eco-friendly farming.

Materials and Methods

A field experiment was conducted at North Farm KITS, Karunya University, Coimbatore, located in Tamil Nadu's Western Ghats zone, during the crop seasons (September - December) of 2022 and 2023. There was a significant amount of rainfall during 2022 when compared to 2023 for September to December (Fig. 1). The soil at the experimental site has a clayey texture and belongs to the vertisol order and the sub-group of typic chromusterts of the Peelamedu series. Soil samples from 0 - 15 cm depth were collected, air-dried, sieved through a 2 mm mesh, and evaluated for physical and chemical characteristics before planting.

A digital pH and EC meter was used to measure the electrical conductivity (EC) and pH of the soil in a (1 : 2) soil-to-water mixture (16).

Soil samples were tested for organic carbon using techniques like chromic acid wet digestion (17), potassium permanganate nitrogen (18), bray phosphorus (19), ammonium acetate potassium (20), neutral normal ammonium acetate cation exchange capacity (21) and DTPA extractant micronutrient analysis (22). Medium black soil with a clayey loam texture (10.40% sand, 30.0% silt, 59.37% clay, pH 8.3, EC 0.34 dS/m and a medium CEC of 18 cmol/kg makes up the experimental site. According to the soil fertility evaluation, the levels of accessible potassium (K), available phosphorus (P), available nitrogen (N) and soil organic carbon (SOC) are 334.3 kg/ha, 216.6 kg/ha, 29.5 kg/ha and 4.8 g/ha respectively (Table 1). In addition to preserving the physical health of the soil and crop quality, the SOM is crucial for preserving soil fertility and production, particularly through the cycling, retention and release of vital plant nutrients. Nitrogen (N) is typically the nutrient of most concern because it has a strong influence on cereal crop productivity. It is a major nutrient composed of cellular parts, amino acids, proteins, enzymes, vitamins and hormones and is a constituent of many enzyme

Fig. 1. Location of experimental field. **Source:** GeoMap

systems that govern various plant metabolic activities (23, 24). Phosphorus (P) responses include the development of lateral roots and root hairs, as well as more striking root structures like proteoid and dauciform roots, the release of phosphatases and organic acids from roots, the induction of high-affinity and some low-affinity inorganic phosphate (Pi) transporters, and the formation of symbiotic relationships with mycorrhizal fungi that facilitate P acquisition (25).

Although potassium (K) is not a component of proteins, it is an essential component of metabolic transport and protein synthesis, and its availability may increase the grain's protein capacity. K has been shown to influence nitrate uptake and assimilation and enhance crop N use efficiency (26, 27). Additionally, potassium increases the amount of protein and amino acids in seeds (28, 29) and contributes to their ability to withstand moisture stress (30, 31).

Mean temperatures in the experiment were between 28 and 39 °C during the day and between 22 and 19 °C at night. The relative humidity in 2022 and 2023 ranged from 55 - 65%, and on 19 and 25 rainy days, the total rainfall was 298.8 mm and 680 mm respectively (Fig. 2).

The experiment used 15 treatment combinations, determining (Table 2) the optimal amounts of potassium, phosphorus and nitrogen for pearl millet yield based on the planned applications.

The amount of potassium, phosphorus and nitrogen needed for the pearl millet yield were calculated using the planned applications as directed. The seed sowing was done 30 days after the application of half of the nitrogen dose. Farmyard manure was incorporated into the plots before planting, adhering to the treatment guidelines. Using urea, single super phosphate and muriate of potash respectively, nitrogen, phosphorus and potassium were provided. To maintain the spacing, the pearl millet seedlings were thinned 10 days after they were sowed, using a 45 × 15 cm spacing. The growth and yield parameters were evaluated at 30, 60 and 90 days after sowing (DAS).

Table 1. Physico-chemical properties of the soil at the start of the experiment - 2022

Property	Value
Texture	Clayey Loam
pH (1:2)	8.3
EC (dS/m)	0.34
Organic carbon (g/ha)	4.8
Available N (kg/ha)	334.3
Available P (kg/ha)	216.6
Available K (kg/ha)	29.5

The research data included measurements of plant height (cm), ear head length (cm), girth (cm), test weight, leaf area index, tiller count, dry matter yield (kg/ha) and effective tillers. Using a SPAD-502 meter (Minolta Co. Ltd., Japan), the amount of chlorophyll in the leaves was measured. After harvesting, the produce from each net plot was hand-threshed, and the seeds were collected through winnowing; these were then weighed individually and documented in kg per plot, which was converted to yield in kg ha^{-1} by using a conversion factor.

The plant's height was determined by measuring from the ground level to the apex. Ten plants were taken out of each plot to determine the indication. The net plot area was used to measure each plant from ground level to the apex of the plant at physiological maturity. The means were then reported as plant height. The final weight is worked out after subtracting of seed yield and recorded as stover yield kg/plot.

The economics of treatments were done by calculating variable costs (VC) on FYM, Vermicompost, seeds, chemical and micronutrient fertilizers and labour separately etc. The gross return (GR) was worked out by multiplying the economic output (pearl millet grain) by the current market price. The net income (NR) was calculated as per Equation 1 and expressed in Rupees (₹) /day. The benefit-cost ratio was determined by dividing net income by the variable cost (Equation 2).

Net income (₹) = Gross returns (₹) - Variable cost (₹) (Eqn 1)

BCR = Net return / Variable cost (Eqn 2)

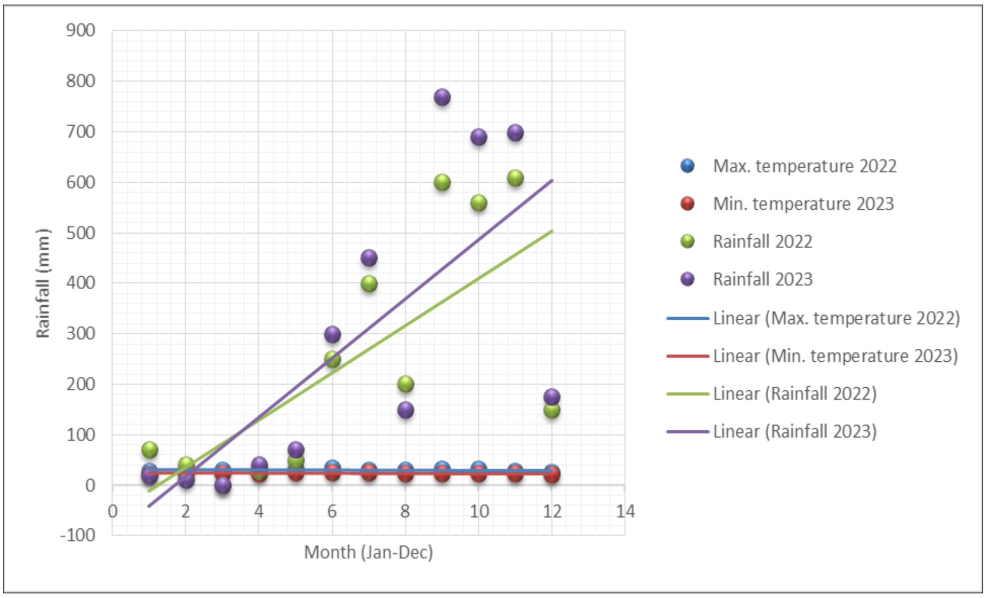


Fig. 2. Weather prevailed during the cropping season.

Results and Discussion

Growth attributes

The nanoemulsion biofertilizer (*Azotobacter* + PSB) significantly increased plant height, tiller count, dry matter accumulation, LAI and chlorophyll index compared to other biofertilizer treatments (Table 3).

Plant height

The study measured plant height at the harvest stage, revealing significant differences among the treatments. The application of nanoemulsion biofertilizer (F3) at 10 mL/L. Produced the tallest plants at the harvest stage, measuring 198.85 cm. This was statistically superior to all other treatments. The application of nano DAP (F1) resulted in the lowest plant height at the harvest stage among the treatments.

The impact of treatment (F3) can mitigate drought stress on millets by enhancing growth and yield through mechanisms like osmotic adjustment, antioxidant activity, phytohormone production and nutrient uptake (32). The application of major nutrients and Vermicompost enhances soil nitrogen availability, promotes vegetative growth through cell multiplication and elongation and increases pearl millet plant height. These results align with those reported in earlier research (33). Organic manures offer both macro-nutrients and micronutrients, gradually releasing them during crop growth, accelerating metabolic processes and improving crop performance (34). The application of nano biofertilizer in plants colonizes their rhizosphere, enhancing their growth by increasing the availability of nutrients (35). Chemicals released by these organisms promote plant growth, perform phosphate and potassium solubilization (36, 37) and fix nitrogen in the soil (38). Phytohormones that support plant growth and development, such as gibberellins, abscisic acid, indole-3-acetic acid, and cytokines are produced by nano biofertilizers (39, 40).

No. of tillers per plant

Table 2 shows that applying nanoemulsion biofertilizer (F3) at 10 mL/L resulted in 6.10 tillers per plant, significantly different from other treatments. The nano DAP (F1) treatment resulted in the lowest count of tillers per plant.

The F3 treatment produced the greatest quantity of tillers per plant throughout all growth stages, attributed to the enhanced availability of plant nutrients. The rise in the number of tillers per plant could be linked to the positive impacts of Vermicompost and macronutrients on vegetative development, which promotes sustained and greater nutrition availability for the crop (41, 42). The organic sources enhanced the efficient utilization of the native as well as added fertilizer nutrients, which maintained a balance between growth and yield attributes.

Leaf area index

During harvest, there were notable differences in the leaf area index (LAI) between treatments. At the harvest stage, the highest LAI was observed in the application of nanoemulsion biofertilizer (F_3) at 10 ml/L with 1.37, which was statistically superior to other treatments. Application of nano DAP (F1) recorded the lowest LAI during the harvest stage. Biofertilizers increase growth hormone release into the rhizosphere, enhancing cell division intensity and leading to increased leaf area and photosynthetic productivity (43).

Dry matter production

The research identified differences in dry matter production (DMP) across various treatments attributed to soil and foliar applications. The study found that the application of nanoemulsion biofertilizer (F3) at 10 mL/L yielded the highest DMP at 7093.46 kg/ha, while the nano DAP (F1) application yielded the lowest.

The F3 treatment resulted in the highest dry matter production due to soil nutrient availability and gradual mineralization, while the combined application improved crop nutrient absorption by enhancing the native microbial population in the soil (44). Applying nutrients, organic fertilizers and nanoemulsion biofertilizers enhanced plant photosynthetic activity, chlorophyll synthesis, nitrogen metabolism and auxin levels, all of which led to an increase in dry matter production. These results are consistent with those seen in earlier reports (45, 46).

The pooled analysis revealed significantly higher values for plant height (198.85 cm) and dry-matter accumulation (7093.46 kg/ha) with foliar feeding as opposed to soil application at harvest. Plants with better nutrition may grow taller since it is necessary for cell division and growth. The plants' enhanced photosynthetic activity may contribute to a greater buildup of dry matter. Bio-products improve the nutritional uptake efficiency of plants and increase crop performance when applied directly to soils or as foliar applications. They disintegrate quickly and oxidize readily with changes in land use (47, 48).

The incorporation of nanoemulsion biofertilizer with organic fertilizer significantly increased plant growth parameters due to increased substrate availability, microbial activity and soil enzyme release (49).

Chlorophyll (SPAD value)

The chlorophyll index at harvest stage is shown in Table 2. The nanoemulsion biofertilizer was found to have the highest chlorophyll index (F3) at 10 mL/L, with values of 32.36 at harvest stage.

The data revealed notable variations when assessed against the other treatments. The treatment with nano DAP (F1) exhibited the lowest chlorophyll index. Furthermore, due to its plant growth-promoting traits, *Azotobacter* combined with PSB could boost nutrient availability and absorption by colonizing the rhizosphere, which in turn enhances chlorophyll levels, an essential element in the synthesis of chlorophyll (50-52).

Yield attributes

Total no. of effective tillers per plant

Table 4 displays the total number of effective tillers per plant recorded at the harvest stage. At the harvest stage, the highest total no. of effective tillers per plant was recorded in the application of nanoemulsion biofertilizer (F3) at 10 mL/L with 5.33, which differed statistically from the other treatments. The nano DAP (F1) resulted in a minimal total number of effective tillers per plant.

Table 2. Detailed treatment information for integrated nutrient management and nano fertilizer applications in pearl millet

Factor: 1 (Soil Application)	
S_1	100% RDF (70:35:35 kg/ha)
S_2	75% RDF + FYM at 10 t/ha
S_3	75% RDF + Vermicompost at 5 t/ha
S_4	50% RDF + FYM at 10 t/ha
S_5	50% RDF + Vermicompost at 5 t/ha
Factor: 2 (Foliar Application)	
F_1	Nano- DAP (2 foliar sprays at 0.2% at 30 and 45 DAS)
F_2	Nano- urea (2 foliar sprays at 2% at 30 and 45 DAS)
F_3	Nano- emulsion biofertilizer (2 foliar sprays at 10 ml/L at 30 and 45 DAS)

Table 3. Influence of nano fertilizers on growth and physiological parameters of pearl millet (two season mean data)

Treatments	At harvest stage				At 60 DAS to harvest stage Crop growth rate (g/m/ day)	Peak flowering stage Chlorophyll (SPAD value)
	Plant height (cm)	No. of tillers/plant	Leaf area index	Dry matter production (kg/ha)		
Soil application (S)						
S_1	162.63	4.90	1.18	5721.06	5.20	24.75
S_2	166.12	4.85	1.21	5834.74	5.30	25.51
S_3	169.49	4.92	1.24	5924.7	5.38	25.83
S_4	172.54	5.01	1.25	6059.20	5.50	26.12
S_5	182.44	5.29	1.37	6379.27	5.78	27.63
SEd	2.02	0.083	0.02	55.62	0.05	0.31
CD (p=0.05)	4.14	0.171	0.04	113.94	0.10	0.64
Foliar application (F)						
F_1	141.98	3.93	0.82	4928.62	4.49	19.55
F_2	171.11	4.89	1.28	5929.34	5.38	25.99
F_3	198.85	6.10	1.66	7093.46	6.43	32.36
SEd	2.61	0.108	0.03	71.81	0.06	0.40
CD (p=0.05)	5.35	0.220	0.06	147.10	0.13	0.82
Interaction (S×F)						
SEd	4.52	0.186	0.05	124.38	0.11	0.70
CD (p=0.05)	9.27	0.382	0.10	254.79	0.23	1.43

Earhead length

The application of nanoemulsion biofertilizer (F3) at 10 ml/L resulted in the highest earhead length (24.34 cm), while nano DAP (F1) resulted in the lowest length (17.56 cm).

Earhead girth

The measurement of earhead girth was conducted at the time of harvest, revealing notable differences among the various treatments. At the harvest stage, the application of nanoemulsion biofertilizer (F3) at a concentration of 10 ml/L resulted in the highest earhead girth of 3.41 cm, which was statistically better than all the other treatments. Application of nano DAP (F1) recorded the lowest earhead girth during the harvest stage.

Test weight

The findings showed that the maximum test weight (14.44 g) was achieved with the use of nanoemulsion biofertilizer (F3) at a concentration of 10 ml/L, and this result was significantly better than many other treatments. The minimum test weight was noted with the nano DAP (F1), which recorded 9.23 g.

The yield attributes were observed significantly higher in S5 + F3 treatment, attributed to the availability of space, light, nutrients and water in sufficient amounts and having limited disturbance of habitat, fixed atmospheric nitrogen, and utilized by pearl millet and increased growth and yield attributes and overall increase the yield. Similar results were reported earlier (53, 54). The combined use of organic manure and bio-fertilizers on cereal fodder such as pearl millet demonstrated a significant improvement in growth characteristics like plant height, the number of tillers per plant, and the number of leaves per plant, resulting in a higher green forage yield in both composite cultivars and hybrids of pearl millet compared to the control. These findings align with the findings of (55). Effective tillers, ear head length, and test weight all rose as a result of the foliar application of nano urea and nanoemulsion biofertilizer (*Azotobacter* + PSB).

The yield characteristics in nano DAP were found to be the lowest because of enhanced nitrogen availability resulting from *Azotobacter*/*Azospirillum*, along with a rise in the solubilization of both native and phosphorus by PSB. Plant growth-promoting rhizobacteria (PGPR) like Azotobacter and PSB enhance nutrient uptake and availability, thereby increasing overall yield through nodulation and growth hormone production (56, 57). The increase in yield attributes through biofertilizers inoculation might be due to inoculation increased the roots through better root development, nodulation, nutrient availability resulting in vigorous plant growth which resulted in better flowering and increase in sink capacity both in size and numbers.

The nano biofertilizer, containing Zn nanoparticles, significantly boosts plant growth, resulting in significant increases in height, leaf count, weight, cob weight and biological weight increases by 42%, 35%, 15%, 10% and 4% respectively (58).

Yield

Grain yield

The grain yield measured at the harvest stage is presented in Table 4. The maximum grain yield was observed with the nano emulsion biofertilizer (F_3), reaching 3175.47 kg/ha at the time of harvest. The data exhibited significant differences compared to all other treatments. The treatment of nano DAP (F_1) resulted in the lowest grain yield of 2308.30 kg/ha. The treatment with foliar application of nano emulsion biofertilizer (F_3) at 10 mL/L at 30 and 45 DAS recorded 19.53% and 37.56% higher grain yield than nano urea and nano DAP foliar applications.

Organic fertilizers such as VC boost INM treatments by enhancing microbial biomass levels, promoting soil enzyme activity, and increasing the net mineralization of organic nitrogen, which results in better outcomes. The results are in line with the findings of (59). Nano biofertilizers improved plants' ability to withstand stress, boosted the biomass of both roots and shoots, and raised the number of productive tillers, the weight of rice grains, as well as nutrient availability and absorption by the plants, all of which directly influence grain yield (60). Nutrient uptake enhances nutrient accumulation and translocation to developing ear heads, resulting in improved filling and grain weight, leading to higher yields (61). Nitrogen applications with biofertilizers enhance plant roots' cation exchange capacity, nutrient absorption efficiency, and growth parameters, leading to higher yields (62). Nano emulsion biofertilizer inoculations improve nitrogen fixation and nutrition, promoting growth and re-translocating seeds for yield components. Our findings are confirmed with those of the earlier report (63).

Stover yield

The nanoemulsion biofertilizer (F3) treatment at 10 mL/L yielded the highest stover yield (6529.99 kg/ha), surpassing all other treatments. The lowest stover yield (4367.21 kg/ha) was noted with the application of nano DAP foliar treatment. Increased organic manure application can decrease soil water evaporation, improve soil moisture retention and provide both macro- and micronutrients (64). A balanced nutrient supply enhances growth, tillering and leaf area, leading to increased stover yields (65). Higher straw yield of pearl millet at integrated nutrient levels of fertilizer could be attributed to enhanced vegetative growth with respect to plant height and tillers/plant. Stover yield can be improved by producing more dry matter, height and leaf area. Seed bacterization in inorganic fertilizers combined with nano biofertilizers is beneficial due to nitrogen fixation, hormone release, enhanced plant growth-promoting substances and improved nutrient uptake. Comparable findings were also documented in an earlier study (66). Use of biofertilizer led to higher availability of N and P that promoted growth and development and ultimately resulting in stover yield (67).

Harvest index

The findings showed that the application of nano emulsion biofertilizer (F_3) at a rate of 10 mL/L yielded the highest harvest index (34.61), markedly outperforming all other treatments. In contrast, the lowest harvest index was found with the nano DAP foliar application (F_4), which was recorded at 32.76. The Nano emulsion biofertilizer may increase harvest index due to increased photosynthetic energy production, which eventually divides to grains instead of straw. The similar results were reported earlier (68).

Interaction

Grain yield was found to be significantly impacted by the application of foliar and soil fertilizers (Table 5). According to the study, the highest grain production (3424.38 kg/ha) was obtained by combining 50% RDF + VC at 5 t/ha with nanoemulsion biofertilizer at 10 mL/L. The increased grain yield can be attributed to the positive impact of combining reduced chemical inputs with Vermicompost as organic sources. Vermicompost with 50% RDF in early growth stages promotes vegetative growth, high yield, chlorophyll formation and protein content, directly increasing plant performance (69).

Table 4. Influence of nano fertilizers on yield attributes and yield of pearl millet (two season mean data)

Treatment	Yield attributes				Yield		
	Total No. of effective tillers/ plant	Earhead length (cm)	Earhead grith (cm)	Test weight (g)	Grain yield (kg/ha)	Stover yield (kg/ha)	Harvest index
Soil application (S)							
S_1	4.28	20.10	2.76	11.54	2632.65	5147.37	32.84
S_2	4.34	20.32	2.82	11.73	2656.44	5297.18	33.05
S_3	4.41	20.50	2.90	11.89	2699.52	5375.40	33.51
S_4	4.49	20.88	2.95	11.94	2725.63	5555.96	33.56
S_5	4.73	22.23	3.03	12.40	2853.10	5876.96	33.95
SEd	0.04	0.35	0.03	0.14	26.68	64.71	0.250
CD (p=0.05)	0.09	0.72	0.07	0.28	54.65	132.55	0.153
Foliar application (F)							
F_1	3.61	17.56	2.28	9.23	2308.30	4367.21	32.76
F_2	4.41	20.52	2.99	12.03	2656.63	5454.52	32.78
F_3	5.33	24.34	3.41	14.44	3175.47	6529.99	34.61
SEd	0.06	0.46	0.04	0.18	34.44	83.54	0.323
CD (p=0.05)	0.12	0.93	0.09	0.36	70.55	171.12	0.662
Interaction (S×F)							
SEd	0.10	0.79	0.08	0.30	59.65	144.69	0.560
CD (p=0.05)	0.20	1.6	0.16	0.62	122.20	296.39	NS

NS: Non-significant

Relationships between dependable variable (plant height) and the predictors (DMP and Grain yield)

The production of dry matter (DMP) and yield in plants results from complex physiological processes that are affected by environmental conditions. The research found that combining 50% RDF + VC with Nano emulsion biofertilizer (S_5F_3) significantly improved DMP formation and grain yield. Plant height, a measure of solar radiation energy and a source of photo assimilates, significantly influences DMP and grain yield. This is indicated by a strong positive influence (15th point - Y= 1.9750), than other variables (Fig. 3).

The effectiveness of the plant in transforming solar radiation energy into biomass greatly influences its overall yield. This relationship was supported by the high regression value (*r* = 0.998) observed between dry matter production (DMP) and grain yield, which reflects the quantity of nano emulsion biofertilizer produced. The leaves synthesized nano emulsion biofertilizer, which supports plant function and contributes to yield formation, was further utilized by plants. This was evidenced by the regression standardized residual that ranges from 0.1912 - 1.5795 (Fig. 3).

Economics of pearl millet cultivation

The economics associated with cultivating pearl millet were notably affected by the interaction of soil and foliar application methods. The combination of 50% RDF and Vermicompost at 5 t/ha with a nano emulsion biofertilizer yielded the highest benefit-cost ratio (2.46), net returns (Rs. 81273/ha) and gross returns (136975.34/ha) among the different soil and foliar treatments (Table 6). Our results are consistent with earlier studies, which suggest that the optimal net returns are achieved by integrating both organic and inorganic fertilizers with PSB (60).

Conclusion

The productivity and quality of pearl millet in clayey loam soils may be improved by adopting best management practices. Two foliar applications at 30 and 45 days after sowing (DAS) of nanoemulsion biofertilizer showed a significant effect on the quality characteristics and productivity of pearl millet. Applications of nanoemulsion biofertilizer at 10 mL/L significantly increased the growth parameters, grain and stover yield, and yield attributes over other treatments.

However, 50% RDF + Vermicompost at 5 t/ha gave comparable results to nanoemulsion biofertilizer at 10 mL/L for growth parameters, grain and stover yield and yield attributes. Applying nanoemulsion biofertilizer at 10 mL/L helped to improve all the quantitative parameters of pearl millet over soil applications (S). Relative to S, the nanoemulsion biofertilizer coupled with 50% RDF + Vermicompost at 5 t/ha increased plant height, dry matter production, number of tillers, earhead length, earhead girth, test weight, grain and stover yield and ranged from 3.84 - 11.2%, 1.54 - 10.22%, 1.59 - 13.67%, 2.29 - 14.02%, 1.33 - 5.74%, 0.77 - 8.92%, 0.32 - 8.96%, 2.65 - 11.21% respectively.

Applying 50% RDF + FYM at 10 t/ha coupled with nanoemulsion biofertilizer increased the grain yield of pearl millet by 0.59% and 1.25% over only 75% RDF + Vermicompost at 5 t/ha with nanoemulsion biofertilizer and 75% RDF + FYM at 10 t/ha with nanoemulsion biofertilizer respectively. Our results suggest that the mode of foliar application, level of nanoemulsion foliar application played a key role in enhancing pearl millet yield. Our study concludes that the application of nanoemulsion biofertilizer at 10 mL/L during both kharif and rabi seasons coupled with 50% RDF +

Table 5. Interaction effect of soil and foliar application on grain yield of pearl millet (two season mean data).

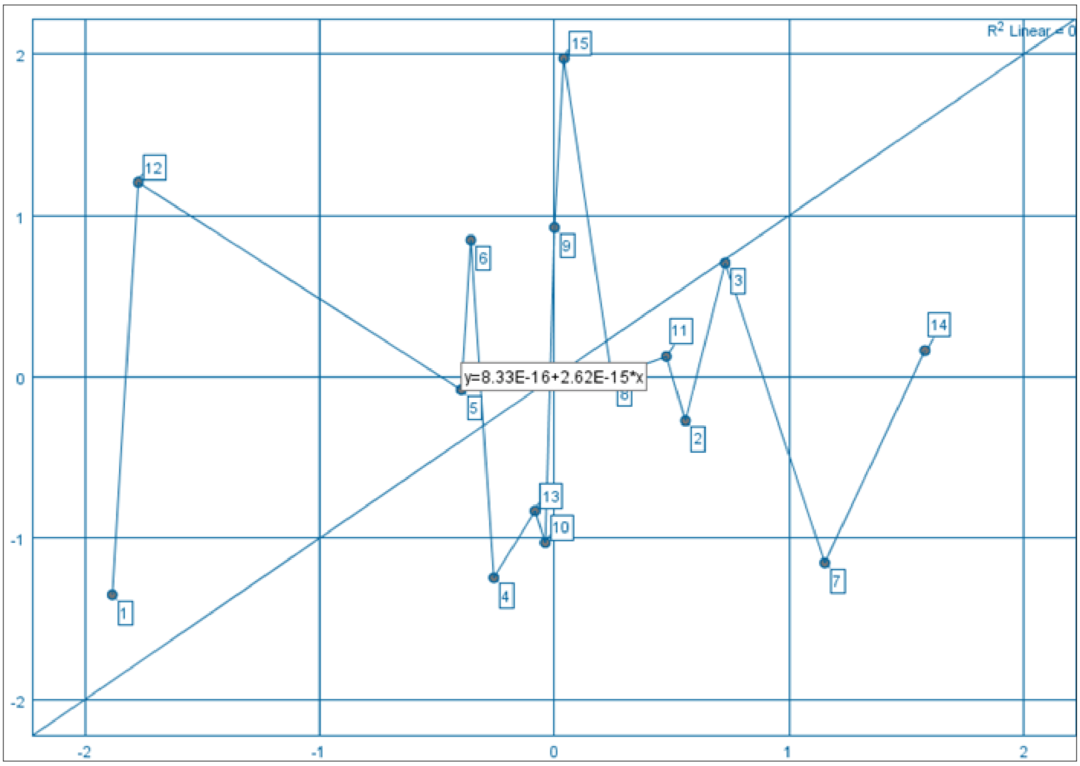
Grain yield (kg/ha)	S_1	S_2	S_3	S_4	S_5	Mean
Treatment						
F_1	2273.33	2280.67	2322.67	2323.48	2341.33	2308.296
F_2	2541.99	2584.89	2651.91	2710.81	2793.58	2595.792
F_3	3082.63	3103.76	3123.98	3142.60	3424.38	3010.852
Mean	2632.65	2280.67	2699.52	2725.63	2853.097	2638.3133
		SE(d) ±			CD (P=0.05)	
S X F		59.65			122.20	

S1 -100% RDF, S2 - 75% RDF + FYM at 10 t/ha, S3 - 75% RDF + VC at 5 t/ha, S4 - 50% RDF + FYM at 10 t/ha, S5 - 50% RDF + VC at 5 t/ha, F1 - Nano DAP, F2 - Nano Urea and F3 - Nano emulsion biofertilizer respectively.

Table 6. Influence of nano fertilizers on economics of pearl millet (two season mean data)

Treatment	Gross returns (Rs.)	Net returns (Rs.)	BCR
S_1F_1	90933.33	11000.33	1.14
S_1F_2	101679.42	28706.42	1.39
S_1F_3	112000.00	46027.00	1.70
$S_2 F_1$	91226.67	13788.67	1.18
$S_2 F_2$	103395.54	32232.54	1.45
$S_2 F_3$	124150.44	60437.44	1.95
S_3F_1	92906.67	16723.67	1.22
S_3F2	106076.41	35988.41	1.51
S_3F_3	124959.20	62646.20	2.01
S_4F_1	92939.22	17916.22	1.24
S_4F_2	108432.40	39819.40	1.58
S_4F_3	125704.09	64691.09	2.06
S_5F_1	93653.33	19710.33	1.27
S_5F_2	111743.20	44295.20	1.66
S_5F_3	136975.34	81273.34	2.46

S1:100% RDF (70:35:35 kg/ha); S2:75% RDF + FYM at 10 t/ha; S3:75% RDF + Vermicompost at 5 t/ha; S4:50% RDF + FYM at 10 t/ha; S5:50% RDF + Vermicompost at 5 t/ha; F1: Nano- DAP (2 foliar sprays at 0.2% at 30 and 45 DAS); F2: Nano- urea (2 foliar sprays at 2% at 30 and 45 DAS); F3: Nano- emulsion biofertilizer (2 foliar sprays at 10 ml/L at 30 and 45 DAS).



Regression model summary:

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.998[a]	.997	.996	1.531

a. Predictors: (Constant), VAR00002, VAR00003

b. Dependent Variable: VAR00001

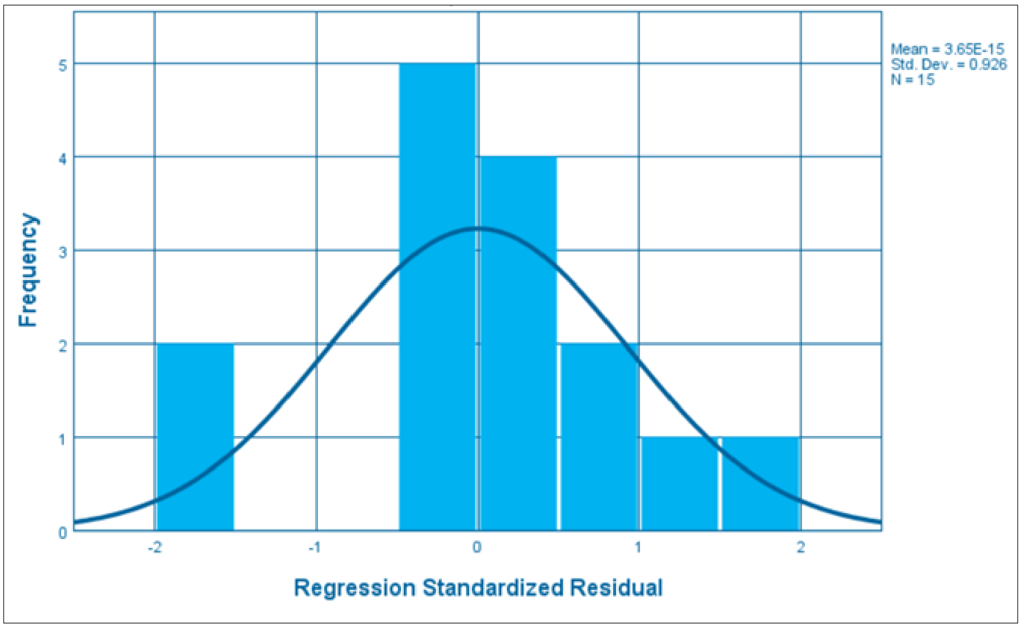


Fig. 3. Interaction effect between 2 factors (Dependent variable (1 no.) - Plant height; Predictors (Constant - 2 nos.): DMP & Grain yield).

Vermicompost at 5 t ha^{-1} improved most of the growth parameters, yield attributes and productivity of pearl millet in these clayey loam soils of Western Ghats.

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Authors' contributions

MKS conducted the experiment. RA participated in the design of the experiment and edited the manuscript. MSA participated in the design of the study and performed the statistical analysis. TD and RSAK participated in its design and coordination.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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