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Response of biofertilizers and multi-micronutrient application on growth and yield of pearl millet (*Pennisetum glaucum* L.)

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Abstract

The field experiment was conducted at the Agricultural Research Farm, Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Bundelkhand University, Jhansi, Uttar Pradesh during the *Kharif* season of 2025-2026. The experiment was laid out in a Randomized Block Design (RBD) consists of ten treatment combinations i.e. T₀ (Control), T₁(Grade I + PSB), T₂(Grade II + PSB), T₃(Grade III + PSB), T₄ (Grade IV + PSB), T₅(Grade V + PSB), T₆(Grade I + Azospirillum), T₇(Grade II + Azospirillum), T₈(Grade III + Azospirillum), T₉(Grade IV + Azospirillum), T₁₀(Grade V + Azospirillum) with three replications. Among the treatments, T₈(Grade III + Azospirillum) recorded maximum plant height (53.52, 147.27, 203.50 cm), dry matter accumulation (12.18, 49.42, 83.86 g per plant) and number of tillers per plant (2.72, 4.85, 4.56) at 30, 60 and 90 DAS, respectively. Maximum leaf area index (3.30) and effective tillers per plant (3.06) were recorded in T₈. Yield and yield attributes were also maximum under T₈, viz., panicle length (26.20 cm), grains/panicle (2148), test weight (10.66), grain yield (3194 kg/ha), stover yield (6587.23 kg/ha) and biological yield (9781.46 kg/ha) of pearl millet

Keywords: Treatment, azospirillum, PSB and grade

1. Introduction

Pearl millet (*Pennisetum glaucum* L.) has gained renewed importance because of its adaptability to arid and semi-arid environments and its significant contribution to the food and nutritional security of millions of smallholder farmers. The crop thrives under conditions of limited rainfall, high temperatures and poor soil fertility, making it the hardiest warm-season cereal crop (Reddy *et al.*, 2013) [15]. Owing to these unique characteristics, pearl millet plays a crucial role in sustaining agricultural production in marginal and rainfed ecosystems.

Globally, pearl millet ranks sixth among cereal crops after rice, wheat, maize, barley and sorghum in terms of cultivated area (Khairwal *et al.*, 2007) [12]. It contributes nearly 42% of the world's total millet production (FAOSTAT, 2024) [8]. In India, pearl millet is the fifth most important cereal crop after rice, wheat, maize and sorghum (Yadav *et al.*, 2011) [23]. It is cultivated on more than 7.57 million hectares, ranking fourth among cereals after rice, wheat and maize (Agricultural Statistics at a Glance, 2021) [1]. The crop serves as a dual-purpose cereal, providing nutritious grains for human consumption and high-quality fodder for livestock, thereby supporting farming systems in arid and semi-arid regions. Consequently, enhancing pearl millet productivity directly impacts the livelihoods of small and marginal farmers, who constitute the majority of its cultivators. Among the pearl millet-growing states, Rajasthan is the leading producer, contributing approximately 27% of India's total production, followed by Karnataka and Maharashtra, contributing 18% and 14%, respectively. Other major producing states include Gujarat, Madhya Pradesh, Haryana and Uttar Pradesh. In Uttar Pradesh, pearl millet is an important kharif crop cultivated over approximately one million hectares, particularly in semi-arid regions, contributing nearly 12% of the national millet production, primarily in the form of bajra (Singh *et al.*, 2019; Agricultural Statistics at a Glance, 2021) [19, 1]. Pearl millet is nutritionally superior to many other cereal crops owing to its high content of dietary fibre, essential amino acids, iron and other

minerals. Its low glycaemic index and rich nutritional composition make it particularly beneficial for individuals suffering from diabetes and cardiovascular diseases (Yadav *et al.*, 2011) [26]. Moreover, its superior nutritional quality offers considerable potential for the development of value-added health foods for both rural and urban consumers.

Despite its resilience and nutritional advantages, pearl millet productivity remains constrained by poor soil fertility and imbalanced nutrient management. One of the major limitations to sustainable crop production is the excessive dependence on macronutrient fertilizers, particularly nitrogen (N), phosphorus (P) and potassium (K), with inadequate supplementation of essential micronutrients. Such imbalanced fertilizer use has resulted in widespread micronutrient deficiencies, declining crop productivity and deterioration in grain nutritional quality (Fageria *et al.*, 2011) [7]. Deficiencies of zinc (Zn), iron (Fe), boron (B), copper (Cu) and manganese (Mn) have become increasingly prevalent in Indian soils, particularly under alkaline conditions where nutrient availability is substantially reduced (Singh *et al.*, 2018; Marschner, 2012) [18, 13].

Micronutrients, although required in small quantities, are indispensable for normal plant growth and development. Iron (Fe) is essential for chlorophyll synthesis and electron transport, while manganese (Mn) functions in enzyme activation and photosystem II activity. Zinc (Zn) plays an important role in auxin synthesis, protein metabolism and enzyme activation. Copper (Cu) is involved in photosynthesis, reproductive development and lignin synthesis, whereas boron (B) is required for cell wall formation, carbohydrate translocation, pollen germination and seed development. Deficiencies of these micronutrients result in poor vegetative growth, impaired grain filling and significant yield reduction. Therefore, balanced micronutrient nutrition is essential for enhancing crop productivity and improving grain quality. In recent years, biofertilizers have emerged as environmentally friendly and cost-effective alternatives to chemical fertilizers for sustainable crop production. Biofertilizers are microbial inoculants that improve soil fertility and crop productivity by enhancing nutrient availability and uptake (Vessey, 2003) [21]. Among the commonly used biofertilizers, phosphate-solubilizing bacteria (PSB) and *Azospirillum* have shown considerable potential in improving nutrient use efficiency and crop performance. Phosphate-solubilizing bacteria (PSB) convert insoluble forms of soil phosphorus into plant-available forms through the production of organic acids, thereby improving phosphorus availability, root development, photosynthesis and ultimately crop productivity (Rodríguez & Fraga, 1999) [16]. *Azospirillum* is an associative nitrogen-fixing bacterium that colonizes the rhizosphere and enhances plant growth by fixing atmospheric nitrogen, promoting root proliferation and synthesizing plant growth regulators such as indole acetic acid (IAA) (Bashan and de-Bashan, 2010) [4]. Soil organic matter (SOM) improves the structure, ability to hold water and nutrient cycling of soil (Yadav *et al.*, 2026a) [24]. The combined application of PSB and *Azospirillum* has been reported to improve nutrient uptake, enhance soil fertility, reduce dependence on chemical fertilizers and increase crop productivity. The integration of biofertilizers with micronutrient application represents a sustainable and synergistic approach to nutrient management. Biofertilizers improve nutrient solubilization, biological nitrogen fixation and nutrient uptake efficiency, whereas micronutrients regulate essential physiological and biochemical processes required for plant growth and development. Hydrophilic gels or hydrogels, are cross-linked polymers-either physically or chemically bound-that can absorb

and retain large volumes of water without dissolving in the soil. Their hydrophilic nature, due to the presence of carboxylic groups, allows them to bind cations and hold water (Yadav *et al.*, 2026b) [25]. Their combined application enhances plant growth, grain yield, nutrient uptake and grain nutritional quality, thereby contributing to both food and nutritional security. Furthermore, integrated use of biofertilizers and micronutrients improves fertilizer use efficiency, lowers production costs, enhances soil health and minimizes environmental degradation, making it particularly beneficial for small and marginal farmers. Integrated Nutrient Management (INM) is a holistic approach that aims to maintain soil fertility and ensure an optimum supply of plant nutrients through the combined use of inorganic fertilizers, organic manures and biofertilizers. INM improves nutrient use efficiency, sustains soil productivity, enhances biological activity and supports long-term agricultural sustainability. Considering the increasing prevalence of micronutrient deficiencies, the need to reduce excessive dependence on chemical fertilizers and the importance of improving productivity and nutritional quality of pearl millet, integrating biofertilizers with micronutrient supplementation has emerged as a promising and sustainable nutrient management strategy. Therefore, evaluating the combined effect of phosphate-solubilizing bacteria (PSB), *Azospirillum* and micronutrients on the growth, yield, nutrient uptake and quality of pearl millet is essential for developing economically viable and environmentally sustainable production technologies.

2. Materials and Methods

The experiment was conducted at the research farm of the Rainfed Agriculture Research Farm, Narayan Bagh, Institute of Agricultural Sciences, Bundelkhand University, Jhansi (U.P.), during *kharif* season 2025. The experimental site is situated in the Bundelkhand region of Uttar Pradesh, which falls under the semi-arid agro-climatic zone. The region is characterized by hot and dry summers, moderate monsoons and cool winters. The area receives an average annual rainfall of approximately 800–900 mm, most of which occurs during the monsoon season (July to September). The climatic conditions of Jhansi are typically semi-arid, with high temperatures during summer months and relatively cooler winters.

3. Results and Discussion

3.1. Growth parameters

The application of different micronutrient grades in combination with biofertilizers significantly influenced the growth attributes of pearl millet throughout the crop growth period. Plant height increased progressively with advancing crop age and significant differences among treatments were observed at 30, 60 and 90 DAS. At 30 DAS, plant height ranged from 42.49 cm under the unfertilized control (T_0) to 53.52 cm under T_8 (Grade III – Zn + *Azospirillum*). Similarly, at 60 DAS, plant height varied from 117.94 cm (T_0) to 147.27 cm (T_8), while at 90 DAS it ranged from 162.60 cm (T_0) to 203.50 cm (T_8). Among all the treatments, T_8 (Grade III – Zn + *Azospirillum*) recorded the maximum plant height at all three growth stages and was significantly superior to the remaining treatments, whereas the unfertilized control (T_0) consistently produced the shortest plants.

The significant improvement in plant height under Zn supplementation in combination with *Azospirillum* may be attributed to the crucial role of zinc in tryptophan synthesis, which serves as a precursor for indole-3-acetic acid (IAA), thereby promoting cell division and elongation. In addition, zinc activates several enzymatic systems involved in physiological and

metabolic processes, while *Azospirillum* enhances biological nitrogen fixation and produces plant growth-promoting substances that stimulate root development and nutrient uptake. The combined effect of these factors resulted in vigorous vegetative growth and greater plant height. Similar findings were reported by Kadivala *et al.* (2019) ^[11] and Angel *et al.* (2023) ^[12]. The number of tillers per plant was also significantly influenced by the combined application of micronutrients and biofertilizers. The highest number of tillers per plant (4.85) was recorded under T₈ (Grade III – Zn + *Azospirillum*), followed by T₃ (4.55) and T₆ (4.36). The enhanced tillering observed under Zn + *Azospirillum* may be attributed to the increased availability of biologically fixed nitrogen coupled with the physiological role of zinc in auxin biosynthesis, which promotes the development and activation of axillary meristems. Moreover, *Azospirillum* produces phytohormones such as indole-3-acetic acid (IAA), gibberellins (GA) and cytokinins, which stimulate root growth, improve nutrient uptake and encourage the initiation and development of tillers. These findings are in close agreement with those of Bhargavi *et al.* (2021) ^[5], who reported that inoculation with *Azospirillum* enhanced root growth and increased tiller production in pearl millet.

Dry matter accumulation was significantly enhanced by the integrated application of micronutrients and biofertilizers. The maximum dry matter accumulation (83.86 g plant⁻¹) was recorded under T₈ (Grade III – Zn + *Azospirillum*). The marked superiority of this treatment may be attributed to improved photosynthetic efficiency, enhanced nutrient acquisition and better utilization of both native and applied nutrients. Zinc acts as an essential activator of several enzymes involved in carbohydrate and protein metabolism, while *Azospirillum* promotes extensive root proliferation and facilitates efficient nutrient uptake, resulting in greater synthesis and translocation of photosynthates to various plant parts. These findings corroborate the results of Vamsi and Umesha (2023) ^[20], who reported a plant dry weight of 78.17 g plant⁻¹ in pearl millet under a similar Zn + biofertilizer combination. Likewise, Divya *et al.* (2017) ^[6] also observed the highest dry matter accumulation in pearl millet under the integrated application of 75% RDF along with biofertilizer and vermicompost.

Leaf area index and effective tillers were also significantly influenced by the different treatments. The highest leaf area index (3.30) and maximum number of effective tillers per plant (3.06) were recorded under T₈ (Grade III – Zn + *Azospirillum*). The improvement in leaf area index may be attributed to enhanced cell division, increased chlorophyll synthesis and improved photosynthetic activity resulting from adequate zinc nutrition and the growth-promoting effects of *Azospirillum*. The increased production of effective tillers under the same treatment can be associated with better nutrient availability, enhanced hormonal activity and greater assimilate partitioning towards productive tillers, ultimately contributing to improved crop growth and yield potential.

3.2 Yield attributes and yield attributes

The yield-attributing characters of pearl millet were significantly influenced by the combined application of different micronutrient grades and biofertilizers (Table 1). Panicle length varied from 18.17 cm under the control (T₀) to 26.20 cm under T₈ (Grade III – Zn + *Azospirillum*). Likewise, the number of grains per panicle ranged from 1447 in T₀ to 2148 in T₈, while the 1000-grain weight (test weight) increased from 8.20 g in the control to 10.66 g under T₈. Among all the treatments, T₈ (Grade III – Zn + *Azospirillum*) recorded the maximum panicle length (26.20 cm), grains per

panicle (2148) and test weight (10.66 g) and was significantly superior to the remaining treatments, whereas the unfertilized control (T₀) consistently recorded the lowest values for all the yield-contributing characters.

The superior performance of T₈ may be attributed to the synergistic effect of zinc and *Azospirillum*. *Azospirillum* enhances biological nitrogen fixation, improves nutrient uptake and produces plant growth-regulating substances that promote panicle development and efficient grain filling. Zinc, on the other hand, plays a vital role in the synthesis of tryptophan, the precursor of auxins, activates several enzymes involved in carbohydrate metabolism and improves pollen viability. These physiological and biochemical functions collectively enhance reproductive growth, resulting in longer panicles, a greater number of grains per panicle and higher test weight. Similar findings were reported by Vamsi and Umesha (2023) ^[20], who recorded 2212.69 grains per earhead and a test weight of 10.29 g with *Azotobacter* + *Azospirillum* + 0.5% Zn in pearl millet, closely corroborating the present results.

Kadivala *et al.* (2019) ^[11] also reported a significant increase in ear-head length with multi-micronutrient mixtures containing Zn and Fe. Comparable improvements in panicle length, grains per earhead and test weight following the combined application of micronutrients and biofertilizers have also been documented by Bhargavi *et al.* (2021) ^[5] and Sebastian *et al.* (2021) ^[17].

The combined application of micronutrient grades and biofertilizers also exerted a highly significant influence on grain yield, stover yield and biological yield of pearl millet, whereas the harvest index remained statistically non-significant (Table 1). Grain yield ranged from 2184.21 kg ha⁻¹ under the control (T₀) to 3194.23 kg ha⁻¹ under T₈ (Grade III – Zn + *Azospirillum*), representing an increase of 1010.02 kg ha⁻¹ (46.2%) over the control. Similarly, stover yield increased from 4514.07 kg ha⁻¹ in T₀ to 6587.23 kg ha⁻¹ in T₈. Consequently, biological yield, representing the combined grain and stover yield, ranged from 6698.28 kg ha⁻¹ under the control to 9781.46 kg ha⁻¹ under T₈, reflecting an improvement of 46.0% over the control.

The significant enhancement in grain, stover and biological yields under T₈ may be attributed to the integrated effect of *Azospirillum* and zinc on crop growth and productivity. Biological nitrogen fixation by *Azospirillum* improves nitrogen availability, while zinc enhances enzyme activity, carbohydrate metabolism and efficient translocation of photosynthates from source to sink. Moreover, the substantial improvement in yield-attributing characters, including panicle length, grains per panicle and test weight, contributed directly to higher grain yield. The production of growth-promoting substances by *Azospirillum* further improved root development, nutrient acquisition and overall crop vigour, ultimately resulting in greater biomass accumulation and enhanced economic yield.

Harvest index varied from 32.46 to 32.76% and did not differ significantly among the treatments. The non-significant variation in harvest index indicates that dry matter partitioning between grain yield and total biological yield remained relatively constant despite the marked increase in total biomass production. Thus, improvements in biological yield were accompanied by proportional increases in grain yield without altering the efficiency of assimilate partitioning. A similar non-significant response of harvest index under different nutrient management practices in pearl millet was reported by Yadav and Solanki (2014) ^[22].

The present findings are in close agreement with those of Vamsi and Umesha (2023) ^[20], who reported the highest grain yield of 34.16 q ha⁻¹ (3416 kg ha⁻¹) with *Azotobacter* + *Azospirillum* +

0.5% Zn in pearl millet. Likewise, Sebastian *et al.* (2021) ^[17] recorded the highest grain yield (4684.57 kg ha⁻¹) and stover yield (6604.02 kg ha⁻¹) with NPK @ 80:40:40 + *Azotobacter* + *Azospirillum*. Bhargavi *et al.* (2021) ^[5] also reported the maximum grain yield (2955 kg ha⁻¹) and stover yield (5867 kg ha⁻¹) with 75% STBN + 25% vermicompost + *Azospirillum* @ 5 kg ha⁻¹. Similarly, Kadivala *et al.* (2019) ^[11] observed the highest

grain yield (2291 kg ha⁻¹) under Grade III multi-micronutrient mixture containing Zn, Fe, Mn, Cu and B. The present results are further supported by the findings of Jain *et al.* (2018) ^[10] and Angel *et al.* (2023) ^[3], who also reported significant improvements in yield and yield-attributing characters of pearl millet through integrated application of micronutrients and biofertilizers.

Table 1: Effect of micronutrient grades and biofertilizers on Growth of pearl millet

Treatments	Plant height (cm)			Dry matter accumulation (g/plant)			Number of tillers per plant		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
T ₀ – Control (RDF only)	42.49	117.94	162.60	8.21	32.56	58.55	1.79	3.19	3.00
T ₁ – Grade I (Fe) + PSB	48.36	135.34	186.02	10.49	41.98	73.08	2.30	4.09	3.81
T ₂ – Grade II (Mn) + PSB	46.55	130.33	179.58	9.79	39.44	69.37	2.15	3.84	3.54
T ₃ – Grade III (Zn) + PSB	50.20	141.50	195.42	11.41	46.42	79.60	2.56	4.55	4.25
T ₄ – Grade IV (Cu) + PSB	45.73	128.15	177.22	9.49	37.98	67.61	2.08	3.70	3.46
T ₅ – Grade V (B) + PSB	47.22	132.02	181.33	10.11	40.51	71.53	2.20	3.94	3.70
T ₆ – Grade I (Fe) + Azospirillum	49.52	138.89	190.93	10.90	44.02	76.51	2.42	4.36	4.04
T ₇ – Grade II (Mn) + Azospirillum	48.06	134.05	184.30	10.30	41.01	72.12	2.29	4.04	3.81
T ₈ – Grade III (Zn) + Azospirillum	53.52	147.27	203.50	12.18	49.42	83.86	2.72	4.85	4.56
T ₉ – Grade IV (Cu) + Azospirillum	46.94	130.64	179.74	9.72	38.94	68.97	2.12	3.81	3.55
T ₁₀ – Grade V (B) + Azospirillum	48.75	136.16	187.83	10.58	42.73	74.58	2.35	4.20	3.92
S.Em ±	0.846	1.34	2.29	0.183	0.801	1.666	0.053	0.136	0.120
CD at 5%	2.497	3.95	6.75	0.539	2.363	4.916	0.158	0.400	0.354

Table 2: Effect of micronutrients grades and biofertilizers on Growth of pearl millet

Treatments	LAI at 60 DAS	Effective Tillers / plant
T ₀ – Control (RDF only)	2.16	1.80
T ₁ – Grade I (Fe) + PSB	2.82	2.50
T ₂ – Grade II (Mn) + PSB	2.68	2.28
T ₃ – Grade III (Zn) + PSB	3.08	2.83
T ₄ – Grade IV (Cu) + PSB	2.58	2.19
T ₅ – Grade V (B) + PSB	2.73	2.40
T ₆ – Grade I (Fe) + Azospirillum	2.92	2.62
T ₇ – Grade II (Mn) + Azospirillum	2.77	2.42
T ₈ – Grade III (Zn) + Azospirillum	3.30	3.06
T ₉ – Grade IV (Cu) + Azospirillum	2.65	2.25
T ₁₀ – Grade V (B) + Azospirillum	2.86	2.48
S.Em ±	0.079	0.083
CD at 5%	0.233	0.245

Table 3: Effect of micronutrients grades and biofertilizers on yield attributes and yield of pearl millet

Treatments	Panicle Length (cm)	Grains / Panicle	Test Weight (g)	Grain Yield (kg/ha)	Stover Yield (kg/ha)	Biological Yield (kg/ha)
T ₀ – Control (RDF only)	18.17	1,447	8.20	2184.21	4514.07	6698.28
T ₁ – Grade I (Fe) + PSB	22.80	1,831	9.50	2760.34	5690.93	8451.26
T ₂ – Grade II (Mn) + PSB	21.51	1,741	9.16	2620.10	5425.74	8045.84
T ₃ – Grade III (Zn) + PSB	24.47	1,990	10.10	2986.11	6182.85	9168.97
T ₄ – Grade IV (Cu) + PSB	20.76	1,699	8.95	2542.40	5288.75	7831.15
T ₅ – Grade V (B) + PSB	22.02	1,780	9.30	2682.08	5566.46	8248.54
T ₆ – Grade I (Fe) + Azospirillum	23.60	1,897	9.80	2855.88	5910.47	8766.35
T ₇ – Grade II (Mn) + Azospirillum	22.21	1,809	9.39	2731.28	5648.94	8380.22
T ₈ – Grade III (Zn) + Azospirillum	26.20	2,148	10.66	3194.23	6587.23	9781.46
T ₉ – Grade IV (Cu) + Azospirillum	21.23	1,717	9.05	2596.45	5374.23	7970.68
T ₁₀ – Grade V (B) + Azospirillum	22.99	1,861	9.56	2794.86	5750.28	8545.14
S.Em ±	0.395	35.29	0.117	42.05	94.78	83.75
CD at 5%	1.166	104.09	0.346	124.05	279.61	247.07

4. Conclusion

The present investigation concluded that the integrated application of biofertilizers, phosphorus and zinc significantly enhanced soil fertility, nutrient availability and overall crop productivity under Bundelkhand agro-climatic conditions. Among the various treatments, the combined application of higher levels of phosphorus and zinc along with biofertilizers

proved most effective in improving soil organic carbon, available nitrogen, phosphorus and potassium status after harvest. The improvement in soil health parameters may be attributed to enhanced microbial activity, better nutrient solubilization, biological nitrogen fixation, and gradual nutrient release from integrated nutrient sources. Biofertilizers such as PSB and Rhizobium played an important role in improving nutrient

availability and uptake efficiency. The study clearly demonstrated that integrated nutrient management involving inorganic fertilizers and biofertilizers is a sustainable and economically viable approach for improving soil fertility and maintaining long-term agricultural productivity.

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