EFFECT OF DIFFERENT LEVELS OF PHOSPHORUS AND BIOFERTILIZERS ON YIELD, UPTAKE AND MICROBIAL ACTIVITY OF FINGER MILLET (ELEUSINE CORACANA)

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ABSTRACT
A study entitled was conducted during summer 2025-26 at Faculty of Agricultural Sciences, Siksha O‘ Anusandhan (Deemed to be University), Bhubaneswar, Odisha to study the Effect of different levels of Phosphorus and Biofertilizers on growth, yield, uptake and microbial activity of Finger millet (Eleusine coracana) in Lateritic soils of Odisha‖. The study was conducted in laboratory using laterite soil collected from experimental field. The experiment was laid out in randomized block design (RBD) with three replications, and it consisted of the following nine treatments. In the soil phosphorus applied in two levels i.e., 75% and 100% inoculated with biofertilizers like phosphorus solubilizing bacteria (PSB) and vascular arbuscular mycorrhiza (VAM) was applied in different combination of treatments in the soil. In this study, it was observed that Treatment T9 (100% RDP + PSB + VAM) consistently outperformed other treatments. It recorded the highest soil pH (7.12), soil EC(0.16dSm-1), OC(0.75%), nitrogen (248.06 kg/ha), phosphorus (31.47 kg/ha), potassium (181.84 kg/ha). T9 also showed maximum nutrient uptake, including nitrogen (83.53 kg/ha), phosphorus (18.4 kg/ha), and potassium (76.84 kg/ha). Growth parameter such as plant height, root length of plant, leaf area index, chlorophyll content, tillers per m2 (315), dry matter accumulation(41.46) ,test weight(3.16g/1000seeds) were significantly higher in T9 compared to the control treatment T1. The yield parameters such as highest grain yield (30.36q ha-1), highest Biological yield (93.34 q ha-1), highest Strover yield (66.44q ha-1), highest Harvest index(32.48%), was observed in T9. The highest protein content found in T9 (7.63) followed by T6(7.56). In case of microbial population (46.84 CFU g-1), PSB population (33.13 CFU g-1), Dehydrogenase activity (135.02 µg TPF g/day) found highest in T9 compared to the control (T1), which consistently recorded the lowest values across all parameters. These results highlight the critical role of phosphorus fertilization and biofertilizer integration in improving crop performance. Overall, the findings demonstrate that integrated nutrient management, particularly the combination of RDP, PSB, and VAM (T9), significantly enhanced soil fertility, plant growth, and yield attributes compared to the control. This study underscores the importance of adopting biofertilizers as sustainable strategies to improve nutrient availability, enhance biomass accumulation, and increase protein content, thereby contributing to higher productivity and soil health in crop production systems.

KEYWORDS: phosphorus, biofertilizers, yield, uptake, nutrient status.

INTRODUCTION
Finger millet is an important food crop of the Asia and Africa semi-arid tropics and an integral part of dry-land farming systems. It is named from the form of the seed head, resembling human fingers (Kerr et. al., 2014; Pokharia et. al., 2014 and Goron et. al., 2015). An important characteristic of finger millet is its adaptability to diverse agro-climatic conditions. It is well adapted to high altitudes and grows in the Himalayas at an elevation of up to 2400 m (NRC, 1996). Its adaptability to drought has been proven: it is drought-tolerant (Dass et. al., 2013 and Hegde et. al., 1986), resistant to diseases, especially many fungal and viral diseases (Kerr et. al., 2014), effective in suppressing weed growth (Samarajeewa et. al., 2006), and can grow on
marginal lands with poor soil fertility. Most of the soils where finger millet is grown are deficient in macro and micronutrients primarily owing to continuous cropping, bad recycling of crop residues, and low rates of organic matter application which can limit yield potential (Rao et. al., 2012). This grain surpasses many cereals in terms of nutritional value, boasting substantial protein, fiber, calcium, and other minerals. Apart from its nutritional richness, finger millet exhibits drought resistance and resilience against diseases, enabling it to thrive across various climatic conditions.
Soil acidity has been recognized as an important problem, globally, which adversely
affects the crop production, directly or indirectly, especially in temperate and tropical regions of the world. Low phosphorus (P) availability and a high P fixation by huge quantities of aluminum (Al) and iron (Fe) oxides are characteristic of highly weathered acid soils in the tropics (Rajneesh et. al., 2018). Large amount of iron and aluminum oxides rapidly react with applied phosphate and make it less soluble in the acidic soils (Ma et. al. 2001; Bolan et. al., 2003). On the other hand, phosphorus deficiency is a major limiting factor for crop production in acidic soils of tropical highlands where soils adsorb large quantity of P and increase the fertilization requirement of crops (Sanchez et. al., 1997; Sato, 2003). Phosphorus (P) is an essential element for plant growth, but its labile forms in soil are relatively scarce compared to those of other major macronutrients (Jain et.al. 2012), because soil compounds and minerals containing P are

naturally of low solubility. Also in certain soils, fertilizer-derived P tends to become progressively less soluble over time Eghball et. al. 1996), in some cases even within a few days after fertilizer placement. This means that even if P is applied at levels normally sufficient for maximum crop yield, there is a strong possibility that it will become a restraining factor due to poor availability (Elser and Haygarth 2020). Biofertilizers are products containing beneficial microorganisms that enhance agricultural production by improving nutrient availability and supply. Among them, phosphorus biofertilizers play an important role in mobilizing the unavailable phosphorus pool in the soil, making it accessible for plant uptake. The introduction of phosphorus- solubilizing microorganisms (PSB) into the rhizosphere increases phosphorus availability from otherwise insoluble phosphate sources through the desorption of fixed phosphates and the secretion of organic acids, thereby improving the efficiency of phosphatic fertilizers. Similarly, Vesicular Arbuscular Mycorrhiza (VAM) forms a mutualistic association with plant roots, developing an extensive network of mycelia that enhances phosphorus uptake, improves soil enzyme activity, and contributes significantly to the phosphorus cycle (Kumar et al., 2017). Biofertilizers are inexpensive, easy to use, and environmentally friendly, making them an effective alternative for sustainable nutrient management. Their judicious use in combination with recommended doses of chemical fertilizers helps maintain crop productivity, improve soil health, and reduce dependence on chemical fertilizers. Considering these advantages, the present investigation was undertaken to evaluate the combined effect of phosphatic fertilizers and biofertilizers (PSB and VAM) on soil enzyme activity and grain yield of finger millet.

MATERIALS AND METHODS

An incubation study entitled "Effect of different levels of Phosphorus and Biofertilizers on growth, yield, uptake and microbial activity of Finger millet (Eleusine coracana) in Lateritic soils of Odisha" was conducted during Kharif 2025-26 at Agricultural Research Station, Binjhagiri, Chhatabar, Faculty of Agricultural Sciences (FAS), Siksha O Anusandhan (Deemed to be University), Bhubaneswar Odisha. Raising a healthy nursery is the first and crucial step in the successful cultivation of transplanted finger millet. A separate, well-drained, fertile plot close to a water source is selected for the nursery. The land is ploughed to a fine tilth, and raised beds of 1 meter width and convenient length are prepared with 30 cm spacing between beds for irrigation and drainage. Before sowing, seeds should be treated with Bavistin to prevent seedling diseases. Seeds were line sown (in 10–15 cm spaced rows) on 4th July and lightly covered with soil and sieved FYM. The bed is mulched with dry grass or straw to retain moisture and protect the emerging seedlings from direct sunlight and desiccation. Light irrigation is applied immediately after sowing, followed by regular watering to maintain optimal soil moisture. The seedlings become ready for transplanting within 21 to 25 days of sowing when they attain 3–4 leaf stage and a height of around 10–12 cm. The composite soils sample thus collected were air dried, sieved through 2 mm sieve and stored in polythene bag,

subjected to mechanical, physical and chemical analysis for obtaining initial analysis data using standard analytical procedure. The initial physico-chemical properties of experimental soil having acidic in pH (5.5), sandy loam in texture, 0.53% organic carbon, low in available nitrogen (78.50kg/ha), medium in available phosphorus (25.92 kg/ha), high in available potassium (175 kg/ha). Recommended dose of fertilizer (kg/ha) N: P: K: 40: 20: 20 was applied. At the time of final land preparation, the full dose of phosphorus and nitrogen and potassium was applied per the treatments. Fertilizers are broadcast uniformly and incorporated into the soil to avoid nutrient loss. Biofertilizers like Phosphorus solubilizing bacteria (PSB) @ 750 ml ha-1 and Vesicular Arbuscular Mycorrhizae (VAM) @ 12.5 kg ha-1 was applied. The experiment was laid out in randomized block design (RBD) with three replications, and it consisted of the following eight treatments. The experimental data collected were subjected to Fisher method of Analysis of variance‖ (ANOVA) as outlined by Panse and Sukhatme (1967).

RESULTS AND DISCUSSION

Effect of different levels of phosphorus and biofertilizers on soil pH, EC, OC soil sample after harvesting the crop

In this study it was observed that soil pH increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels but declined with low application. In lateritic soils, it was found that the pH value ranged from 5.8 to 7.12. The data presented in Table 1 shows that the maximum pH was recorded in treatment T9 – (100% RDP + PSB + VAM), which was significantly superior to treatments T1, T2, T3, T4, T5, T7 and T8, but statistically at par with T6 (75% RDP + PSB + VAM). The minimum pH (5.48) was recorded in T1 (no phosphorus). This gradual decline in soil pH during crop growth stages can be attributed to root exudation of organic acids and enhanced microbial activity, particularly by phosphate- solubilizing bacteria (PSB), which produce acids like gluconic acid to solubilize phosphorus, thereby acidifying the rhizosphere (Chen et al., 2006). The combined application

of biofertilizers further accelerates acidification due to microbial oxidation of elemental sulphur to sulphuric acid (Kandpal et al., 2019).

It was observed that soil EC increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels but declined with low application. The maximum EC (0.16 dS/m) was observed in T9, which was significantly better than treatments T1, T2, T3, T4, T5, T7 and T9, but statistically similar to T6 and T8. The minimum EC (0.09 dS/m) was recorded in T1. The gradual decline in EC over the crop growth period may be attributed to nutrient uptake by plants, leaching of soluble salts, and improved microbial assimilation of ions, the higher EC observed in T6, T8 and T9 treatment may be due to the solubilization of phosphorus and sulphur compounds by phosphate-solubilizing bacteria (PSB) and VAM, which increase the concentration of ionic species in the soil solution, Conversely, the control treatment, lacking nutrient amendments and biofertilizers, maintains a lower ionic concentration, resulting in the lowest EC throughout the stages (Wahane et. al. 2022 and Elizabeth et. al. 2018).

Table 1. pH , EC and available OC content of harvested soil

Treatment	pH	EC(dSm-1)	OC(%)
T1 - No phosphorus	5.48	0.09	0.39
T2 - 75% STD	5.63	0.10	0.45
T3 - 100% STD	5.81	0.10	0.48
T4 - 75% RDP + PSB	6.14	0.11	0.51
T5 - 75% RDP + VAM	6.42	0.12	0.55
T6 - 75% RDP + PSB + VAM	7.14	0.15	0.69
T7 - 100% RDP + PSB	6.82	0.13	0.57
T8 - 100% RDP + VAM	6.95	0.14	0.62
T9 - 100% RDP + PSB + VAM	7.12	0.16	0.75
SE(m)+	0.12	0.01	0.07
CD(0.05)	0.35	0.02	0.20
CV(%)	3.19	9.43	20.73

It was observed that soil OC increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels but declined with low application. T9 recorded the highest OC (16.90%), significantly outperforming T1, T2 and T4 and was statistically on par withT5, T6, T7 and T8. The lowest OC (0.39%) was observed in T1. PSB and VAM nitrogen fixation and root biomass production, which contributes to higher organic matter input in the soil (Kaur et al., 2005). PSB not only solubilize bound phosphorus but also secrete polysaccharides that support microbial biomass and organic matter retention (Zaidi et al., 2009). Additionally, PSB and VAM indirectly improves SOC by enhancing soil structure and promoting microbial activity (Kandpal et al., 2019). The gradual decrease in SOC from flowering to harvest could be due to increased mineralization and decomposition of organic matter during crop growth (Bhattacharyya et al., 2013). Wahane et. al. (2022).

Effect of different levels of phosphorus and biofertilizers on available nutrient status (kg/ha):
It was observed that soil N increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table 2) but declined with low application. The highest N (248.06 Kg/ha) was recorded in T9, significantly higher to all treatments. The lowest N (198.58 Kg/ha) was found in T1. The overall decreasing trend of available nitrogen during the crop growth period can be attributed to the progressive uptake of nitrogen by plants and possible leaching losses over time (Singh et al., 2011). The significantly higher available nitrogen in treatments T6 may be due to the role of a symbiotic nitrogen-fixing bacterium, which converts atmospheric nitrogen into plant-available forms, thereby enriching the soil nitrogen pool (Zahran, 1999). The presence of PSB may have enhanced root growth and nutrient absorption through improved phosphorus availability, which supports better nitrogen uptake and assimilation (Zaidi et al., 2009). Furthermore, the control plots showed the lowest nitrogen levels due to the absence of nutrient inputs and biological enhancements (Wahane et. al. (2022), Andrei et. al. (2020), Suri et. al. (2011), Elizabeth et. al. (2018), Opala et. al. (2018), Singh et. al. (2017)
It was observed that soil P2O5 increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table 2) but declined with low 300 application. The maximum P2O5 (22.14 Kg/ha) was observed in T9, significantly higher than T1, T2, T3, T4 and T7 but statically with T5, T6 and T8. T1 recorded the minimum P2O5 (9.69 Kg/ha). The decreasing trend of available phosphorus from flowering to harvest is likely due to the progressive uptake of P by the growing crop and potential fixation of P in unavailable forms as the season progresses (Holford, 1997). The significantly higher available P in treatments T5, T6, T8 and T9 can be attributed to the combined application of phosphorus fertilizers, phosphate-solubilizing bacteria (PSB) and VAM. PSB produce organic acids such as gluconic and citric acids, which solubilize the otherwise insoluble phosphorus compounds, thereby increasing the availability of P to plants (Chen et al., 2006). Additionally, the inclusion of PSB in T9 may further support microbial activity and organic acid production through symbiotic interactions, leading to better P availability. In contrast, the control treatment lacked any phosphorus input or microbial inoculants, resulting in the lowest P content throughout all growth stages.
It was observed that soil K2O increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table 4) but declined with low application. T9 had the highest K2O (203.50 Kg/ha), significantly different from T1, T2, T3 and T4 and but at par with T5, T6, T7 and T8. T1 had the minimum K2O (117.01 Kg/ha). The significantly higher levels of available K in T9 and T6 treatments can be attributed to the synergistic effects of biofertilizers PSB, VAM and phosphorus fertilization. Moreover, phosphate-solubilizing bacteria (PSB) and VAM enhance root proliferation and nutrient absorption, indirectly contributing to better uptake and cycling of potassium (Zaidi et al., 2009). The control treatment recorded the lowest available K due to the absence of nutrient inputs and biological activity, limiting K availability and mobility in soil. Wahane et. al. (2022), Andrei et. al. (2020), Suri et. al. (2011), Elizabeth et. al. (2018), Opala et. al. (2018), Singh et. al. (2017)

Table 2. Impact of varying levels of phosphorus and biofertilizer application on post-harvest available soil nutrients (N, P, and K)

Treatment	Available N (Kg/ha-1)	Available P2O5(Kg/ha-1)	Available K2O (Kg/ha-1)
T1 - No phosphorus	198.58	11.25	152.35
T2 - 75% STD	210.89	15.49	158.96
T3 - 100% STD	221.32	18.80	164.62
T4 - 75% RDP + PSB	227.19	21.74	168.45
T5 - 75% RDP + VAM	232.01	23.64	171.81
T6 - 75% RDP + PSB + VAM	242.93	27.99	177.33
T7 - 100% RDP + PSB	237.59	25.80	174.16
T8 - 100% RDP + VAM	241.09	27.23	176.70
T9 - 100% RDP + PSB + VAM	248.06	31.47	181.84
SE(m)+	7.34	0.61	4.27
CD (0.05)	22.01	1.83	12.79
CV (%)	5.56	4.67	4.36

Effect of different levels of phosphorus and biofertilizers on yield (q ha-1)of finger millet

It was observed that grain yield increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 3) but declined with low application. The highest grain yield (30.36 q/ha) was recorded T9, significantly better than all other treatments. T1 had the lowest grain yield (12.47 q/ha). The enhanced yield in T9 and T6 is attributed to the synergistic effect of integrated nutrient management involving phosphorus and biofertilizers (VAM and PSB). Rhizobium inoculation significantly improves nitrogen availability via biological nitrogen fixation, which supports vigorous vegetative growth and biomass accumulation. Phosphorus is essential for energy transfer, cell division, and root development, all of which influence overall plant biomass (Rao & Reddy, 2010). PSB enhances phosphorus solubilization, increasing its availability to the crop. The control treatment yielded the lowest haulm production due to nutrient limitations and lack of microbial activity. (2002), Nishigaki et. al. (2019), Penn and Camberato (2019).

It was observed that grain yield increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 3) but declined with low application. The highest biological yield (93.34 q/ha) was recorded T9, significantly better than all other treatments. T1 had the lowest biological yield (43.62 q/ha). The enhanced yield in T9 and T6 is attributed to the synergistic effect of integrated nutrient management involving phosphorus and biofertilizers (VAM and PSB). Rhizobium inoculation significantly improves nitrogen availability via biological nitrogen fixation, which supports vigorous vegetative growth and biomass accumulation. Phosphorus is essential for energy transfer, cell division, and root development, all of which influence overall plant biomass (Rao & Reddy, 2010). PSB enhances phosphorus solubilization, increasing its availability to the crop. The control treatment yielded the lowest haulm production due to nutrient limitations and lack of microbial activity. (2002), Nishigaki et. al. (2019), Penn and Camberato (2019).

It was observed that grain yield increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 3) but declined with low application. The highest strover yield (66.44 q/ha) was recorded T9, significantly better than all other treatments. T1 had the lowest strover yield (31.22 q/ha). The enhanced yield in T9 and T6 is attributed to the synergistic effect of integrated nutrient management involving phosphorus and biofertilizers (VAM and PSB). Rhizobium inoculation significantly improves nitrogen availability via biological nitrogen fixation, which supports vigorous vegetative growth and biomass accumulation. Phosphorus is essential for energy transfer, cell division, and root development, all of which influence overall plant biomass (Rao & Reddy, 2010). PSB enhances phosphorus solubilization, increasing its availability to the crop. The control treatment yielded the lowest haulm production due to nutrient limitations and lack of microbial activity. (2002), Nishigaki et. al. (2019), Penn and Camberato (2019).

Table 3. Influence of different levels of phosphorus and biofertilizers on the yield parameters of finger millet

Treatments	Grain yield (q ha-1)	Biological yield (q ha-1)	Strover yield (q ha-1)	Harvest index (%)
T1 – No phosphorus	12.47	43.62	31.22	28.43
T2 – 75% STD	18.27	62.89	44.67	29.04
T3 – 100% STD	21.51	71.68	50.12	30.04
T4 – 75% RDP + PSB	21.15	72.58	51.47	29.15
T5 – 75% RDP + VAM	20.15	70.16	49.83	29.02
T6 – 75% RDP + PSB + VAM	25.66	85.77	61.93	29.80
T7 – 100% RDP + PSB	24.62	83.50	58.93	29.51
T8 – 100% RDP + VAM	23.15	80.30	58.90	28.84
T9 – 100% RDP + PSB + VAM	30.36	93.34	66.44	32.48
SE(m)+	1.07	1.61	1.48	1.53
CD(0.05)	3.20	4.84	4.44	4.58

CV(%)	8.43	3.79	4.88	8.93

It was observed that grain yield increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 3) but declined with low application. The highest harvest index (32.48 q/ha) was recorded T9, significantly comes at par with all the treatments. T1 had the lowest harvest index (28.43 q/ha). The enhanced yield in T9 and T6 is attributed to the synergistic effect of integrated nutrient management involving phosphorus and biofertilizers (VAM and PSB). Rhizobium inoculation significantly improves nitrogen availability via biological nitrogen fixation, which supports vigorous vegetative growth and biomass accumulation. Phosphorus is essential for energy transfer, cell division, and root development, all of which influence overall plant biomass (Rao & Reddy, 2010). PSB enhances phosphorus solubilization, increasing its availability to the crop. The control treatment yielded the lowest haulm production due to nutrient limitations and lack of microbial activity. (2002), Nishigaki et. al. (2019), Penn and Camberato (2019).

Effect of different levels of phosphorus and biofertilizers on uptake (kg ha-1)of finger millet

It was observed that plant N increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 4) but declined with low application. T9 recorded the highest N (83.53 Kg/ha), significantly superior to all treatments. The minimum N (32.43 Kg/ha) was found in T1. The superior performance of T9 and T6 treatments can be attributed to the combined application of phosphorus and biofertilizers (VAM and PSB). VAM enhances nitrogen fixation, directly increasing plant nitrogen content, while PSB increases the availability of phosphorus, a nutrient that aids in nitrogen metabolism and overall plant energy flow (Zaidi et al., 2009; Gyaneshwar et al., 2002). The control plot, devoid of these inputs, showed poor nutrient availability and uptake, resulting in lower nitrogen content and uptake. Wahane et. al. (2022), Xuan et. al. (2014), Sushila et. al. (2021), Suri et. al. (2011), Potdar et. al. (2020), Hafner et. al. (1992), Liao et. al. (2020)

Table 4. Influence of different levels of phosphorus and biofertilizers on the uptake (kg ha-1) of finger millet

Treatment	Total N(kgha-1)	Total P2O5(kgha-1)	Total K2O(kgha-1)
T1 - No phosphorus	32.43	4.11	28.53
T2 - 75% STD	48.50	7.89	42.12
T3 - 100% STD	58.27	10.21	52.69
T4 - 75% RDP + PSB	62.03	11.50	55.44
T5 - 75% RDP + VAM	65.40	12.80	58.05
T6 - 75% RDP + PSB + VAM	74.80	15.69	68.29
T7 - 100% RDP + PSB	70.20	14.16	63.54
T8 - 100% RDP + VAM	72.97	14.96	66.00
T9 - 100% RDP + PSB + VAM	83.53	18.40	76.84
SE(m)+	1.55	0.47	2.93
CD (0.05)	4.64	1.40	8.79
CV (%)	4.24	6.65	8.93

It was observed that plant P increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 4) but declined with low application. The highest P (18.4 Kg/ha) was also recorded in T9, significantly superior to all. The minimum P (4.11 Kg/ha) was recorded in T1. Wahane et. al. (2022), Xuan et. al. (2014), Cristian et. al. (2018), Sushila et. al. (2021), Suri et. al. (2011), Potdar et. al. (2020), Hafner et. al. (1992), Kisinyo (2016), Li et. al. (2008), Martin et. al.

It was observed that plant K increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 4) but declined with low application. T9 recorded the maximum K (76.84 Kg/ha), significantly better than T1, T2, T3, T4, T5, T7 and T8 but statically similar with T6. The lowest K (28.53 Kg/ha) was in T1. Wahane et. al. (2022), Xuan et. al. (2014), Cristian et. al. (2018), Sushila et. al. (2021), Suri et. al. (2011), Potdar et. al. (2020).

Response of the total microbia activity to different levels of phosphorus and biofertilizer application in fingermillet

It was observed that grain yield increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 5) but declined with low application.

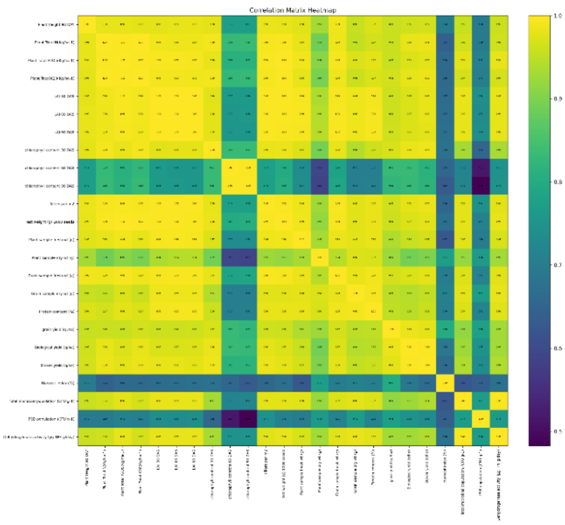
Table 5. Response of the total microbia activity to different levels of phosphorus and biofertilizer application in fingermillet

Treatments	Total microbial population (CFU g-1)	PSB population (CFU g-1)	Dehydrogenase activity (µg TPF g/day)
T1 – No phosphorus	16.47	2.13	45.37
T2 – 75% STD	21.05	3.53	58.04
T3 – 100% STD	23.89	4.27	66.50
T4 – 75% RDP + PSB	32.59	24.24	88.40

T5 – 75% RDP + VAM	34.13	5.30	92.03
T6 – 75% RDP + PSB + VAM	42.09	26.80	112.55
T7 – 100% RDP + PSB	36.20	28.55	98.13
T8 – 100% RDP + VAM	37.53	5.93	104.44
T9 – 100% RDP + PSB + VAM	46.84	33.13	135.02
SE(m)+	1.17	0.77	2.32
CD (0.05)	3.50	2.30	6.97
CV (%)	6.26	8.93	4.53

The highest total microbial population (46.84 CFUg-1) was recorded T9, significantly superior the all the treatments. T1 had the lowest total microbial population (28.43 CFUg-1). Natural fermentation of finger millet (Eleusine coracana) was carried out for 48h. Microbiological and chemical analysis was performed throughout the fermentation process Antony and Chandra 1997). It was observed that grain yield increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table. 7) but declined with low application. The highest total microbial population (33.13 CFUg-1) was recorded T9, significantly superior the all the treatments. T1 had the lowest total microbial population (2.13 CFUg-1) same result was founded by Dida et. al. (2008). It was observed that grain yield increased with increase in phosphorus solubilizing bacteria and vascular arbuscular mycorrhiza application levels (Table 5) but declined with low application. The highest total dehydrogenase activity (135.02 µg TPF g/day) was recorded T9, significantly superior the all the treatments. T1 had the lowest dehydrogenase activity (45.37 µg TPF g/day) same result was founded by Yadav et. al. (2022)

Correlation matrix graph



The correlation matrix heatmap presents the relationships among various plant growth, physiological, yield, nutrient uptake, and soil biological parameters measured during the experiment. The correlation coefficient (r) ranges from 0 to 1, where values closer to 1.00 indicate a very strong positive relationship, meaning that as one parameter increases, the other also increases. The diagonal elements have a value of 1.00, representing the perfect correlation of each variable with itself. The heatmap reveals that most of the measured variables are highly and positively correlated (r = 0.90–1.00). Plant height at 90 DAS, total plant nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) uptake, leaf area index (LAI) at different growth stages, tillers per square meter, test weight, plant biomass, grain biomass, protein content, grain yield, biological yield, and stover yield exhibit very strong positive associations with one another. These strong relationships indicate that improved nutrient uptake enhances vegetative growth, which subsequently contributes to greater biomass accumulation and higher grain production. Chlorophyll content measured at 30 DAS also shows strong positive correlations with most growth and yield traits. However, chlorophyll content at 60 and 90 DAS demonstrates comparatively moderate positive correlations (approximately 0.70–0.83) with several variables, suggesting that chlorophyll concentration during later growth stages is influenced by additional physiological and environmental factors. Among the soil biological parameters, total microbial population and dehydrogenase activity exhibit strong positive correlations with plant growth, nutrient uptake, and yield components. This indicates that greater microbial activity improves soil fertility and nutrient availability, thereby enhancing crop performance. In contrast, the phosphate-solubilizing bacteria (PSB) population shows relatively weaker, though still positive, correlations (approximately 0.68–0.77) with most agronomic traits. Similarly, the harvest index displays moderate positive correlations (around 0.63–0.80), implying that it is influenced not only by biomass production but also by the efficiency of biomass partitioning into grain. Overall, the heatmap demonstrates a strong interdependence among nutrient uptake, plant growth, yield attributes, and soil biological properties, confirming that improved soil health and nutrient availability collectively contribute to enhanced crop productivity.

CONCLUSION

The study clearly demonstrates that the integration of phosphorus fertilization with biofertilizers such as phosphate solubilizing bacteria (PSB) and vesicular arbuscular mycorrhiza (VAM) exerts a significant positive influence on soil properties, plant growth, and grain quality. Across all measured parameters, treatment T9 (100% recommended dose of phosphorus combined with PSB and VAM) consistently outperformed other treatments, highlighting the synergistic effect of chemical and biological inputs. Soil characteristics improved markedly under T9, with the highest pH (7.12), electrical conductivity (0.16 dS/m), organic carbon (16.90%), nitrogen (433.65 kg/ha), phosphorus (22.14 kg/ha), and potassium (203.50 kg/ha). These values were significantly superior to the control (T1), which consistently recorded the lowest values, underscoring the importance of phosphorus and biofertilizer supplementation in maintaining soil fertility. Plant samples under T9 also showed enhanced nutrient uptake and physiological traits. Nitrogen (14.07 kg/ha), phosphorus (0.36 kg/ha), and potassium uptake were highest, accompanied by improved chlorophyll content (36.54), greater biomass accumulation (fresh weight 72.68 g; dry weight 41.46 g), and increased plant height (55.21 cm). Grain samples mirrored these improvements, with maximum fresh weight (32.19 g), dry weight (23.38 g), and protein content (7.63%). These findings confirm that the combined application of PSB and VAM with adequate phosphorus not only enhances nutrient availability but also translates into better crop performance and quality. The control treatment (T1, no phosphorus) consistently exhibited poor outcomes, with minimum soil fertility values, reduced plant growth, and inferior grain yield and protein content. This contrast highlights the critical role of phosphorus fertilization and biofertilizer integration in sustaining productivity. Overall, the results emphasize that integrated nutrient management, particularly the combination of recommended phosphorus dose with PSB and VAM, is a sustainable strategy to improve soil health, maximize nutrient uptake, and enhance yield and quality of crops. This approach offers a promising pathway toward higher agricultural productivity while maintaining ecological balance.

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