

Enhancing soybean seed yield through biopriming with liquid biofertilizers

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ABSTRACT

Liquid biofertilizers, which contain beneficial microorganisms, present a sustainable solution by improving nutrient availability and soil health. A field study was conducted to assess the effects of liquid biofertilizers on soybean seed yield, quality, and soil nutrient status. The experiment followed a randomized block design (RBD) with eight treatments, including recommended rate of fertilizer (RRF: 30:80:37 NPK kg/ha) and seed treatment with various liquid biofertilizers such as effective microorganisms (EM) culture, Potassium solubilizing bacteria (KSB), Phosphate solubilizing bacteria (PSB), *Azospirillum*, *Pseudomonas*, and *Rhizobium*. The liquid biofertilizers were treated at 20 ml/kg of seed. Liquid biofertilizer seed treatments were carried out in addition to the RRF. In the control treatment, no liquid biofertilizer seed treatment was used; only recommended rate of fertilizers were applied. Results indicated that biopriming with liquid biofertilizers significantly enhanced yield parameters such as the number of pods/plant, seed yield/plant, and overall seed yield/hectare. The highest seed yield (2,651 kg/ha) and net returns (₹82,614) were achieved with the EM culture seed-priming followed by PSB (2,633 kg/ha) and *Rhizobium* (2,628 kg/ha). Seed quality metrics, including germination % and vigor indices, were markedly higher in biofertilizer-treated seed plots compared to the control. Post-harvest soil analysis revealed increased levels of available nutrients, microbial biomass carbon and microbial count in plots with seeds treated with biofertilizers, signifying improved soil fertility. Economically, all biofertilizer treatments outperformed only RRF treatment in terms of net returns and benefit-cost ratios. The study concludes that biopriming with liquid biofertilizers is a sustainable and economically viable option for boosting soybean productivity.

Key words: Soybean, Seed yield, Seed quality, Seed vigor, Biopriming, Economics

Soybean (*Glycine max* L.) is a globally significant leguminous crop, renowned for its high protein (40–42%) and oil content (18–22%), making it integral to food security, livestock feed, and industrial applications such as biodiesel production. In India, soybean cultivation is particularly important in Madhya Pradesh, Maharashtra, and Rajasthan, where it contributes significantly to the agricultural economy. One of the key agronomic advantages of soybean is its ability to fix atmospheric nitrogen through symbiosis with rhizobia, playing a crucial role in sustainable cropping systems. However, despite its economic and agronomic importance, soybean productivity in India remains below its potential due to poor soil fertility, declining biological nitrogen fixation (BNF), and inefficient nutrient uptake

(Sharma *et al.*, 2020). Early seedling establishment and vigor are crucial for uniform crop stand, nodulation efficiency, and yield potential (Kumar *et al.*, 2021). Strong early growth enhances root development, nutrient uptake, and stress tolerance, leading to improved productivity (Sannagoudar *et al.*, 2024). Conversely, inadequate seedling vigor can cause poor plant stand, delayed nodulation, and lower nitrogen fixation, ultimately reducing yield. Conventional seed treatments, such as fungicide coatings and synthetic inoculants, provide protection against pathogens but do not actively promote nutrient uptake or stress resilience (Rashid *et al.*, 2004). Moreover, excessive reliance on chemical fertilizers has led to soil degradation, microbial imbalance, and rising production costs. These limitations emphasize the need for biological seed treatments that not only protect the seed but also enhance early growth while maintaining soil health.

Biopriming, an innovative seed treatment that combines seed hydration with microbial inoculation, has emerged as an effective alternative to traditional methods (Meena

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et al., 2020). Unlike conventional seed coatings, bio-priming involves treating seeds with liquid biofertilizers, allowing beneficial microorganisms to colonize the seed surface and establish early symbiotic interactions before sowing. This process enhances seedling emergence, nutrient solubilization, nitrogen fixation, and resilience to environmental stress. Liquid biofertilizers, which contain living microbial inoculants, are particularly effective for biopriming applications due to their high microbial viability, superior seed adherence, and ease of application compared to carrier-based biofertilizers. Beneficial microbial strains such as *Rhizobium*, *Azospirillum*, PSB, and *Pseudomonas* play key roles in enhancing seedling vigor, nodulation, and nutrient acquisition (Sharma *et al.*, 2020). For instance, *Rhizobium*-based biopriming promotes early nodulation, leading to increased nitrogen fixation and better root development. Similarly, PSB solubilizes phosphorus, a critical nutrient for root elongation and pod formation (Yadav *et al.*, 2020). Studies indicate that bioprimed soybean seeds exhibit improved germination, stronger root systems, and greater tolerance to abiotic stress compared to untreated seeds.

Despite the growing recognition of biopriming with liquid biofertilizers, limited research has explored its practical effectiveness in soybean cultivation under field conditions. While earlier studies have evaluated carrier-based biofertilizers, liquid formulations remain understudied, particularly in terms of their impact on plant growth, seed yield, seed quality, and post-harvest soil fertility (Sharifi *et al.*, 2018). Additionally, there is a lack of comparative studies assessing the effectiveness of different microbial strains when applied through biopriming. To address this research gap, the present study evaluates the effectiveness of biopriming soybean seeds with various liquid biofertilizers, focusing on their impact on growth, yield, and seed quality parameters. Specifically, it examines their influence on plant height, SPAD values, and nodulation efficiency, as well as their effects on yield attributes such as pod count/plant, seed yield, and test weight. Additionally, the study assesses the impact of biopriming on seed germination, vigor indices, and post-harvest soil nutrient status, while also determining the economic viability of liquid biofertilizer applications in soybean cultivation. By providing insights into the potential of biopriming as an eco-friendly seed enhancement technique, this research aims to offer a sustainable alternative to conventional seed treatments, reducing the dependency on synthetic fertilizers while improving soybean productivity and soil health.

MATERIALS AND METHODS

Experimental site: The experiment was performed at the ICAR-National Institute of Seed Science and Technol-

ogy, Regional Station, Bengaluru, Karnataka, India [13° 05' N°, 77° 34' E', and 846 mean sea level] during *khari* 2022–23 and 2023–2024. The experimental site soil is reddish brown laterite resulting from genesis under a semi-arid sub-tropical climate. The soil was red sandy loam with a pH of 6.43, organic carbon 0.56%, initial available nitrogen, phosphorus, potassium content of 251.42 kg/ha, 29.88 kg/ha, 183.64 kg/ha respectively.

Experiment details: The experiment was set up in a randomized block design (RBD) with 3 replications, having the following 8 treatment combinations: T₁, No seed treatment, only recommended rate of fertilizers (RRF); T₂, RRF + recommended seed treatment practice (Thiram + Bavistin (2:1) @ 3 g/kg in combination with *rhizobium* @ 5 g/kg seed; T₃, RRF + seed treatment with KSB @ 20 ml/kg seed; T₄, RRF + seed treatment with PSB @ 20 ml/kg seed; T₅, RRF + seed treatment with *Azospirillum* @ 20 ml/kg seed; T₆, RRF + seed treatment with *Pseudomonas* @ 20 ml/kg seed; T₇, RRF + seed treatment with *Rhizobium* culture @ 20 ml/kg seed; T₈, RRF + seed treatment with EM culture @ 20 ml/kg seed. The soybean variety 'JS-335' was used and the seeds were treated with the respective biofertilizers before sowing, a seed rate of 62.5 kg/ha with spacing of 45 cm × 15 cm was followed. The recommended dose of nitrogen, i.e. 30 kg/ha was applied through urea, phosphorus was applied through single super phosphate at the rate of 80 kg/ha and 37 kg/ha potassium was applied through muriate of potash at the time of sowing. For weed management a pre-emergence application of Pendimethalin 30 EC @ 1.5 litres/ha was applied within 24 hours of sowing followed by a hand weeding 40 days after.

Weather pattern: The meteorological data for the sowing experimental site in 2023 and 2024 reveal significant seasonal variations in weather parameters (Fig. 1). Rainfall was highest in October (292.7 mm), followed by May (176.8 mm) and August (143.5 mm), while January and February remained completely dry. The maximum temperature peaked at 36.02°C in April, whereas the lowest

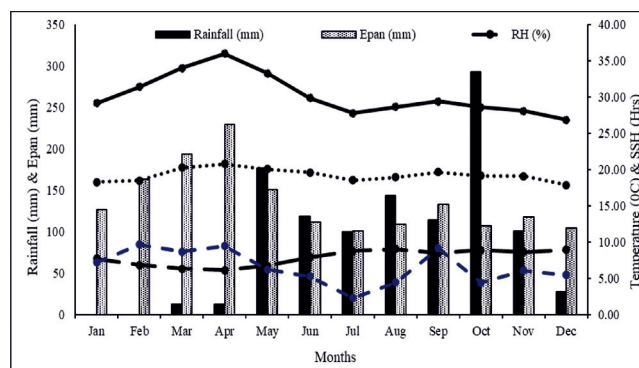


Fig. 1. Mean monthly meteorological data of the experimental site for the year 2023 and 2024

minimum temperature (17.85°C) was recorded in December. Relative humidity ranged from the highest in August (78.92%) to the lowest in April (53.77%). Evaporation was most intense in April (230 mm) and least in December (104 mm). Sunshine hours were at their maximum in February (9.6 hours) and declined to the lowest in July (2.3 hours). These variations indicate distinct seasonal weather patterns that could impact agricultural activities in the region.

Growth attributes: Plant height was measured from the base of the plant to the tip of the tallest leaf at maturity using a measuring tape. Five plants/plot were randomly selected, and the average height was calculated. The number of effective nodules was counted by carefully uprooting five plants/plot at the flowering stage. The nodules were classified as effective based on their reddish-pink internal color and counted/plant.

SPAD reading (Chlorophyll content): Chlorophyll content was assessed using a SPAD meter (SPAD-502) at the flowering and pod formation stages. Five random leaves/plot were selected, and the average SPAD value was recorded. Placing the SPAD meter on the middle part of the fully expanded trifoliate leaf, avoiding the main vein. Five readings from different leaves within the plant were taken, and the average SPAD reading was calculated for each plant. The SPAD readings were taken regularly at weekly intervals between 30–45 DAS and used for analysis.

Yield and yield attributes: At maturity, the number of pods/plant was counted from five randomly selected plants/plot, and the average was calculated for each treatment. Seed yield/plant was determined by harvesting all mature pods from five randomly selected plants/plot. The seeds were separated, weighed, and the average yield/plant was recorded. The total seed yield/plot was calculated by harvesting all plants within the plot, separating the seeds, and weighing the total yield. Seed yield was expressed in kilograms/hectare (kg/ha). Seed recovery percentage was calculated by dividing the weight of graded seed yield by the weight of bulk seed yield and multiplying the result by 100. Test weight (100-seed weight) was determined by randomly selecting 100 seeds/treatment and weighing them using an electronic balance.

Seed quality attributes: Germination tests were conducted under standard laboratory conditions. A sample of 100 seeds/treatment was placed on moist filter paper in Petri dishes and incubated at 25°C. Germination was recorded after seven days, and the percentage of germinated seeds was calculated (ISTA, 2007).

$$\text{Germination \%} = \frac{\text{Number of normal seedlings}}{\text{Number of seeds kept for germination}} \times 100$$

Vigour Index 1 (VI1) was calculated by multiplying the seed germination percentage by the mean seedling length (cm). Vigour Index 2 (VI2) was determined using the same

method by multiplying the seed germination percentage by the mean seedling dry weight (mg).

Available soil nutrient status: Soil samples were collected from each plot at planting and at harvest. The available N, P, and K content in the soil was determined using alkaline permanganate method, Olsen's method and flame photometry method, respectively.

Microbial count, microbial biomass carbon, urease and dehydrogenase activity

The total bacteria, fungi, and actinomycetes in the free rhizosphere were enumerated after the crop harvest using the serial dilution and agar plate method. Soil microbial biomass carbon was assessed using the fumigation-extraction method. Moist soil sub-samples were fumigated with CHCl₃ and subsequently extracted with KSO. The biomass carbon content was determined by calculating the difference in carbon levels between fumigated and non-fumigated samples. Urease activity was assessed using a colorimetric technique outlined by Kandeler, 1996. Dehydrogenase activity was evaluated using a colorimetric method described by Ohlinger *et al.*, 1996.

Economics: Gross returns were calculated by multiplying the seed yield/ha by the market price of soybean at harvest. The total cost of cultivation included expenses for land preparation, sowing, irrigation, fertilization, pest management, and harvesting. Net returns were determined by subtracting the total cost of cultivation from the gross returns/ha. The benefit-cost ratio was calculated by dividing the gross returns/ha by the total cost of cultivation.

Statistical Analysis: The experimental data were analyzed statistically using Analysis of Variance (ANOVA) in a randomized block design (RBD) to assess the significance of treatment effects. Differences among treatment means were evaluated using F-tests, and critical difference (CD) values were computed at a 5% probability level ($p \leq 0.05$) for mean comparison (Gomez and Gomez, 1984). Results were interpreted based on the pooled data of two years.

RESULTS AND DISCUSSION

Vegetative growth performance: During the vegetative phase, seeds treated with EM culture @ 20 ml/kg demonstrated the most vigorous growth, achieving the greatest plant height (56.26 cm), highest SPAD value (44.73), and the largest number of effective nodules/plant (47.33) (Table 1). These results were statistically equivalent to other bio-priming treatments, such as *Rhizobium*, *Azospirillum*, and PSB, but significantly outperformed the conventional fungicidal seed treatment (Thiram + Bavistin 2:1 @ 3 g/kg + *Rhizobium* @ 5 g/kg seeds), which recorded 47.81 cm plant height, 42.44 SPAD value, and

Table 1. Growth parameters of soybean as influenced by biopriming with liquid biofertilizers

Treatment	Plant height (cm)	SPAD value	Number of effective nodules/plant
T ₁ , No seed treatment (ST), only recommended rate of fertilizers (RRF)	41.65	42.00	29.33
T ₂ , RRF + recommended ST (Thiram + Bavistin (2:1) @ 3 g/kg in combination with <i>Rhizobium</i> @ 5 g/kg seed	47.81	42.44	36.67
T ₃ , RRF + ST with KSB @ 20 ml/kg seed	49.99	42.89	39.33
T ₄ , RRF + ST with PSB @ 20 ml/kg seed	53.58	44.13	46.33
T ₅ , RRF + ST with <i>Azospirillum</i> @ 20 ml/kg seed	50.10	43.62	43.67
T ₆ , RRF + ST with <i>Pseudomonas</i> @ 20 ml/kg seed	49.01	42.74	39.33
T ₇ , RRF + ST with <i>Rhizobium</i> culture @ 20 ml/kg seed	50.84	43.83	46.00
T ₈ , RRF + ST with EM culture @ 20 ml/kg seed	56.23	44.73	47.33
SEm±	2.69	0.71	1.91
CD (P=0.05)	8.16	2.16	5.81

36.67 effective nodules/plant (Table 1). The exceptional vegetative growth observed in EM culture-treated seeds manifested as increased plant height, SPAD values, and nodulation can be ascribed to the synergistic actions of the microbial consortium in EM culture. This consortium, comprising photosynthetic bacteria, lactic acid bacteria, and yeast, enhances nutrient availability through mechanisms such as biological nitrogen fixation (BNF), phosphate solubilization, and the synthesis of growth-promoting compounds like Indole-3-Acetic Acid (IAA) and Gibberellins (Kumar *et al.*, 2021; Sannagoudar *et al.*, 2023). These microorganisms also improve root morphology, expanding the root surface area for enhanced nutrient and water absorption (Singh *et al.*, 2020). The comparable performance of *Rhizobium*, *Azospirillum*, and PSB treatments further underscores the significance of specialized microbial functions, such as BNF and phosphorus mobili-

zation, in fostering plant growth (Meena *et al.*, 2020). Conversely, the fungicidal treatment likely inhibited beneficial microbial populations, resulting in diminished nodulation and nutrient assimilation (Patel *et al.*, 2018).

Yield and yield attributes: Post-harvest analysis revealed that EM culture-treated seeds produced the highest number of pods/plant (60.27), a result statistically comparable to *Rhizobium* (54.53) and PSB (56.60) treatments and 19.89% greater than the fungicidal treatment (50.27) (Table 2). Additionally, EM culture led in seed yield metrics, with the highest seed yield/plant (17.67 g)/plot (3.18 kg), and per hectare (2651 kg/ha). These values were statistically on par with other bio-priming treatments but significantly exceeded the control, which recorded the poorest yields (12.84 g/plant, 2.31 kg/plot, and 1927 kg/ha) (Table 2). Among other yield parameters, KSB-treated seeds achieved the highest seed recovery percentage (88.93%),

Table 2. Yield and yield attributes of soybean as influenced by biopriming with liquid biofertilizers

Treatment	No. of pods/plant	Seed yield/plant	Seed yield/plot (kg)	Seed yield (kg/ha)	Seed recovery %	Test weight (g)
T ₁ , No seed treatment (ST), only recommended rate of fertilizers (RRF)	34.93	12.84	2.31	1,927	80.65	131.33
T ₂ , RRF + recommended ST (Thiram + Bavistin (2:1) @ 3 g/kg in combination with <i>Rhizobium</i> @ 5 g/kg seed	50.27	15.56	2.80	2,333	83.67	135.00
T ₃ , RRF + ST with KSB @ 20 ml/kg seed	53.27	15.96	2.87	2,394	88.93	134.33
T ₄ , RRF + ST with PSB @ 20 ml/kg seed	56.60	17.56	3.16	2,633	88.02	138.67
T ₅ , RRF + ST with <i>Azospirillum</i> @ 20 ml/kg seed	53.67	16.33	2.94	2,449	83.55	139.00
T ₆ , RRF + ST with <i>Pseudomonas</i> @ 20 ml/kg seed	50.67	15.64	2.82	2,347	85.82	138.67
T ₇ , RRF + ST with <i>Rhizobium</i> culture @ 20 ml/kg seed	54.53	17.52	3.15	2,628	87.40	139.00
T ₈ , RRF + ST with EM culture @ 20 ml/kg seed	60.27	17.67	3.18	2,651	88.37	142.00
SEm±	1.63	1.27	0.23	191	7.06	3.33
CD (P=0.05)	4.94	3.86	0.69	579	21.43	10.10

though this was statistically similar to all other treatments, including the control (80.65%). The test weight was greatest for EM culture (142.00 g), a result statistically aligned with all treatments except the control (131.33 g). The elevated pod count and seed yield in EM culture-treated seeds can be attributed to the improved nutrient use efficiency and stress resilience facilitated by the microbial consortium (Gupta *et al.*, 2020). EM culture enhances the bioavailability of essential nutrients, including nitrogen, phosphorus, and iron, which are pivotal for reproductive development (Rana *et al.*, 2021). Moreover, the production of exopolysaccharides and biofilm formation by EM microbes mitigates abiotic stresses such as drought and salinity, thereby stabilizing yield under adverse conditions (Sharma *et al.*, 2020). The comparable yields of *Rhizobium* and PSB treatments further highlight the critical role of targeted microbial functions, such as BNF and phosphorus solubilization, in optimizing reproductive growth (Yadav *et al.*, 2020). The inferior yields in the fungicidal treatment and control underscore the limitations of chemical inputs and the absence of microbial support, respectively, in sustaining high productivity.

Germination and seedling vigour

The highest germination rates were observed in EM culture and PSB treatments, both achieving 98.67%. This was statistically equivalent to all other bio-priming treatments but surpassed the conventional fungicidal treatment (96.67%) and the control (94.33%) (Table 3). In terms of seedling vigour, EM culture recorded the highest vigour index I (4004), though statistically similar to all other seed treatments, including the fungicidal treatment (3562) and control (3383). Similarly, vigour index II was greatest for EM culture, statistically matching *Rhizobium* (107.15), PSB (110.50), and *Azospirillum* (106.49), and exceeding the fungicidal treatment (93.15) by 20.20% (Table 3). The

enhanced germination percentage and vigour indices in EM culture and PSB treatments can be linked to the production of plant growth regulators (PGRs) and the mobilization of seed reserves during early growth stages. Microbial inoculants secrete enzymes such as amylases and proteases, which degrade seed endosperm, providing readily available energy for germination (Jogaiah *et al.*, 2020). Additionally, the synthesis of PGRs like Cytokinins and Auxins by EM microbes stimulates cell division and elongation, fostering robust seedling establishment (Kumar *et al.*, 2021). The reduced germination and vigour in the control and fungicidal treatments suggest that the absence of microbial activity or the presence of chemical residues can impair seed metabolism and early growth (Singh *et al.*, 2020).

Post-harvest soil nutrient status

Seed treatments significantly influenced the post-harvest nutrient profile of the soil. The EM culture treatment resulted in the highest soil nitrogen content (273.40 kg/ha), statistically comparable to all other seed treatments but notably higher than the control (224.61 kg/ha) (Table 4). The maximum available phosphorus was detected in the *Pseudomonas* treatment (32.38 kg/ha), though statistically similar to all seed treatments, with the control showing the lowest value (26.95 kg/ha). Similarly, the EM culture treatment recorded the highest available potassium (218.72 kg/ha), statistically exceeding the fungicidal treatment (206.81 kg/ha) and control (179.69 kg/ha) by 21.72% (Table 4). The post-harvest soil analysis revealed that bio-priming treatments, particularly EM culture and *Pseudomonas*, significantly enhanced soil nutrient levels. This can be attributed to the ability of these microbes to fix atmospheric nitrogen, solubilize insoluble phosphates, and mineralize organic matter, thereby improving nutrient cycling and availability (Meena *et al.*, 2020). For instance, *Pseudomo-*

Table 3. Seed quality attributes of soybean as influenced by biopriming with liquid biofertilizers

Treatment	Germination (%)	Vigour index-I	Vigour index-II
T ₁ , No seed treatment (ST), only recommended rate of fertilizers (RRF)	94.33	3383	86.76
T ₂ , RRF + recommended ST (Thiram + Bavistin (2:1) @ 3 g/kg in combination with <i>Rhizobium</i> @ 5 g/kg seed	96.67	3562	93.15
T ₃ , RRF + ST with KSB @ 20 ml/kg seed	97.67	3719	98.68
T ₄ , RRF + ST with PSB @ 20 ml/kg seed	98.67	3962	110.50
T ₅ , RRF + ST with <i>Azospirillum</i> @ 20 ml/kg seed	98.00	3844	106.49
T ₆ , RRF + ST with <i>Pseudomonas</i> @ 20 ml/kg seed	97.00	3675	97.26
T ₇ , RRF + ST with <i>Rhizobium</i> culture @ 20 ml/kg seed	98.33	3948	107.15
T ₈ , RRF + ST with EM culture @ 20 ml/kg seed	98.67	4004	111.97
SEm±	0.60	149	4.38
CD (P=0.05)	1.81	453	13.27

Table 4. Available soil nutrient status soil after harvest of soybean as influenced by biopriming with liquid biofertilizers

Treatment	Avail N (kg/ha)	Avail P (kg/ha)	Avail K (kg/ha)
T ₁ , No seed treatment (ST), only recommended rate of fertilizers (RRF)	224.61	26.95	179.69
T ₂ , RRF + recommended ST (Thiram + Bavistin (2:1) @ 3 g/kg in combination with <i>Rhizobium</i> @ 5 g/kg seed	258.51	31.02	206.81
T ₃ , RRF + ST with KSB @ 20 ml/kg seed	268.52	32.22	214.82
T ₄ , RRF + ST with PSB @ 20 ml/kg seed	261.11	31.33	208.89
T ₅ , RRF + ST with <i>Azospirillum</i> @ 20 ml/kg seed	268.35	32.20	214.68
T ₆ , RRF + ST with <i>Pseudomonas</i> @ 20 ml/kg seed	269.85	32.38	215.88
T ₇ , RRF + ST with <i>Rhizobium</i> culture @ 20 ml/kg seed	266.44	31.97	213.15
T ₈ , RRF + ST with EM culture @ 20 ml/kg seed	273.40	32.81	218.72
SEm±	6.06	1.01	3.30
CD (P=0.05)	18.37	3.06	10.00

nas spp. produce organic acids and siderophores, which chelate iron and other micronutrients, rendering them accessible to plants (Rana *et al.*, 2021). The diminished nutrient levels in the control and fungicidal treatments highlight the adverse effects of chemical inputs on soil microbial communities and nutrient dynamics (Patel *et al.*, 2018).

Soil health: Biopriming with liquid biofertilizers significantly influenced soil microbial populations, microbial biomass carbon (MBC), dehydrogenase activity (DHA), and urease activity after harvest (Fig. 2). The highest bacterial population (65.32×10^6 CFU/g) was observed in the treatment with Effective Microorganism culture, followed closely by *Rhizobium* seed treatment (63.11×10^6 CFU g⁻¹), whereas the lowest bacterial count was recorded in the control treatment without seed priming (40.06×10^6 CFU/g). Similarly, fungal and actinomycetes populations were enhanced significantly with biofertilizer treatments, with EM culture showing the highest counts (18.44×10^4

and 9.22×10^3 CFU g⁻¹, respectively). In contrast, the control treatment had the lowest microbial counts, indicating that biopriming effectively enhanced microbial abundance. MBC, a crucial indicator of microbial activity and organic matter turnover, was maximized in treatments with *Azospirillum* and EM culture (101.11 mg/kg), followed by PSB (100.77 mg/kg), demonstrating the improved soil microbial biomass due to biopriming. The control recorded the lowest MBC (78.89 mg/kg), reinforcing the role of microbial inoculants in enhancing soil health. Enzyme activities, which are vital indicators of soil biological functions, were also significantly improved by biopriming. DHA, which represents microbial oxidative metabolism, was highest in *Azospirillum* and EM-treated soils (61.55 µg TPF/g 24 hrs), followed by PSB (61.34 µg TPF/g 24 hrs) and KSB (61.06 µg TPF/g 24 hrs), whereas the control exhibited the lowest value (45.86 µg TPF/g 24 hrs). Similarly, urease activity, essential for nitrogen mineralization, showed the highest values in *Azospirillum* and EM-treated soils (87.92 µg NH₄+/g 2 hrs), followed closely by PSB and KSB treatments, while the control recorded the lowest value (66.17 µg NH₄+/g 2 hrs). These findings emphasize that biopriming with microbial inoculants significantly enhances soil microbial dynamics and enzymatic processes, leading to improved nutrient cycling and soil fertility (Gupta *et al.*, 2022). The superiority of EM culture in promoting microbial activity suggests its potential as an efficient biofertilizer, contributing to sustainable agricultural practices (Singh *et al.*, 2020).

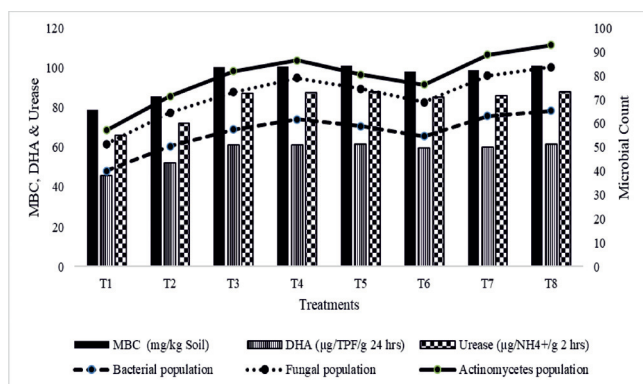


Fig. 2. Soil microbial count, soil microbial biomass carbon (MBC), dehydrogenase (DHA), and urease activity after harvest as influenced by influenced by biopriming with liquid biofertilizers

Economic analysis

Economic evaluation revealed that the EM culture treatment delivered the highest gross returns (₹121,946), net returns (₹82,614), and benefit-cost (B:C) ratio (3.10) (Table 5). These metrics were closely followed by other

Table 5. Economics of soybean cultivation as influenced by biopriming with liquid biofertilizers

Treatment	Gross returns (₹)	COC (₹)	Net returns (₹)	Benefit: cost ratio
T ₁ , No seed treatment (ST), only recommended rate of fertilizers (RRF)	88,642	33,785	54,857	2.62
T ₂ , RRF + recommended ST (Thiram + Bavistin (2:1) @ 3 g/kg in combination with <i>Rhizobium</i> @ 5 g/kg seed	107,318	39,200	68,118	2.74
T ₃ , RRF + ST with KSB @ 20 ml/kg seed	110,124	39,401	70,723	2.79
T ₄ , RRF + ST with PSB @ 20 ml/kg seed	121,118	39,368	81,751	3.08
T ₅ , RRF + ST with <i>Azospirillum</i> @ 20 ml/kg seed	112,654	39,368	73,287	2.86
T ₆ , RRF + ST with <i>Pseudomonas</i> @ 20 ml/kg seed	107,962	39,333	68,630	2.74
T ₇ , RRF + ST with <i>Rhizobium</i> culture @ 20 ml/kg seed	120,888	39,401	81,487	3.07
T ₈ , RRF + ST with EM culture @ 20 ml/kg seed	121,946	39,333	82,614	3.10

bio-priming treatments. In contrast, the control treatment registered the lowest economic performance, with gross returns of ₹88,642, net returns of ₹33,785, and a B:C ratio of 2.62. The cost of cultivation was highest for *Rhizobium* and KSB treatments (₹39,401), followed by PSB and *Azospirillum* (₹39,368), EM culture and *Pseudomonas* (₹39,333), and lowest for the control (₹33,785) (Table 5). The superior economic returns of EM culture-treated seeds evidenced by higher gross returns, net returns, and B:C ratio demonstrate the financial viability of bio-priming as a sustainable alternative to chemical seed treatments. The reduced reliance on synthetic fertilizers and pesticides, coupled with enhanced yields, translates to lower input costs and higher profitability (Sharma *et al.*, 2020). The poor economic performance of the control further emphasizes the necessity of seed treatments to achieve optimal yields and returns in modern agriculture.

Over a two-year field study, liquid biofertilizers significantly improve soybean growth, yield, and seed quality while enhancing soil nutrient levels. The bio-priming with EM culture yielded the highest seed output (2651 kg/ha) and net returns (₹82,614), followed by PSB (T₄) and *Rhizobium* (T₇). Liquid biofertilizers such as PSB, *Azospirillum*, and *Pseudomonas* also enhanced plant growth, nodulation, and seed quality, highlighting their potential as eco-friendly alternatives to chemical fertilizers. Post-harvest soil analysis showed higher concentrations of available nitrogen, phosphorus, and potassium in biofertilizer-treated plots, highlighting their role in improving soil fertility. Economically, all biofertilizer treatments provided higher net returns and benefit-cost ratio compared to the control. In conclusion, liquid biofertilizers are a sustainable and effective approach for increasing soybean productivity, seed quality, and soil health, offering a viable alternative to chemical fertilizers. Future research should focus on optimizing application techniques and assessing long-term impacts on soil and crop systems.

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