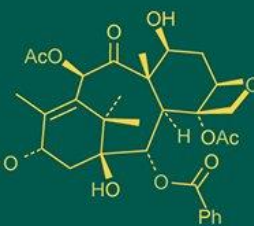
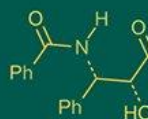


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Influence of microbial consortia and integrated nitrogen management on growth, productivity and economic performance of sorghum (*Sorghum bicolor* L.)

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Abstract

To evaluate the influence of different methods of microbial consortia application and integrated nitrogen management on the growth, productivity and economics of *Kharif* sorghum (*Sorghum bicolor* L.). Field experiment laid out in a factorial Randomized Block Design (RBD) with 16 treatment combinations (four methods of microbial consortia application × four levels of integrated nitrogen management) replicated thrice. Research Farm, Department of Agronomy, Naini Agricultural Institute, Faculty of Agriculture, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj-211007 (U.P.), India, during *Kharif* 2024 and *Kharif* 2025. Sorghum variety Amarnath 2000 was sown at 12 kg seed ha⁻¹ with a recommended fertilizer dose of 80-40-40 kg N-P-K ha⁻¹. Microbial consortia were applied as seed treatment (30 g kg⁻¹ seed), soil application (2.5 kg/50 kg FYM), a combination of both, or omitted (control), each combined with four nitrogen management schedules (100% urea; 50% urea + 50% FYM; 50% urea + 50% vermicompost; 50% urea + 25% FYM + 25% vermicompost). Plant height, Leaf Area Index (LAI) and dry weight were recorded at periodic intervals, and cost of cultivation, gross returns, net returns and Benefit-Cost (B:C) ratio were computed. Data for both years were pooled and analyzed using ANOVA appropriate for RBD. The combined application of seed treatment and soil application of microbial consortia with 50% N through urea + 25% N through FYM + 25% N through vermicompost (T₁₂) produced the tallest plants (190.44 cm at 75 DAS; 239.16 cm at 100 DAS, pooled), the highest LAI (4.84 and 3.92) and the greatest dry weight (100.67 g and 122.94 g plant⁻¹), significantly superior to all other treatments (CD, *p* = 0.05). The lowest values for these growth parameters were recorded under the no-consortia control with 100% N through urea (T₁₃). Economic analysis showed that although T₁₂ gave the highest gross and net returns, the combined seed treatment + soil application of consortia with 100% N through urea (T₉) returned the highest benefit-cost ratio (2.64), reflecting its comparatively lower input cost. Combined seed and soil application of microbial consortia, integrated with a balanced organic-inorganic nitrogen schedule, improved the growth and productivity of *Kharif* sorghum over sole chemical fertilization or the absence of microbial consortia. Growers aiming to maximize plant growth and biomass may adopt the combined consortia application with 50% urea + 25% FYM + 25% vermicompost (T₁₂), while those prioritizing economic return per unit investment may prefer combined consortia application with 100% urea (T₉).

Keywords: Microbial consortia, integrated nitrogen management, sorghum, plant height, leaf area index, dry matter accumulation, nitrogen, fym, vermicompost; growth, economic

Introduction

Sorghum (*Sorghum bicolor* L.) is among the most important dryland cereals of the semi-arid and sub-humid tropics, valued as a source of food, fodder and raw material for the starch and bio-energy industries. Its inherent drought tolerance and adaptability to marginal soils make it a dependable crop for resource-constrained rainfed and irrigated cropping systems across India (Reddy *et al.*, 2023) ^[9]. Nitrogen is the single most yield-limiting nutrient in sorghum production, yet continuous reliance on inorganic nitrogen sources such as urea can deteriorate soil physical and biological properties over time, raise input costs and reduce nitrogen-use efficiency. Integrated nutrient management, in which urea is judiciously combined with organic sources such as farmyard manure (FYM) and vermicompost (VC), has been advocated as a means of sustaining soil fertility while maintaining productivity,

since organic amendments improve soil organic carbon, microbial activity and slow-release nutrient availability alongside the readily available nitrogen supplied by urea. Microbial consortia, comprising complementary nitrogen-fixing, phosphate-solubilizing and other plant-growth-promoting microorganisms, offer a complementary route to improving nutrient-use efficiency. Seed treatment ensures early rhizosphere colonization, whereas soil application throughout the root zone; the combination of both methods has been reported to produce more consistent gains in growth and yield attributes than either method alone (Kavya *et al.*, 2020) ^[5]. Similar synergistic effects of microbial inoculation with organic amendments on growth and biomass accumulation have been documented in *Kharif* sorghum under rainfed conditions (Kakde *et al.*, 2020) ^[4] and in other cereals receiving integrated nutrient sources (Tshering *et al.*, 2023; Negi *et al.*, 2022) ^[7, 11]. While the individual effects of microbial consortia and of integrated nitrogen management on sorghum have received attention, information on their combined, factorial influence on growth, dry matter accumulation and, importantly, the economics of cultivation remains limited under the specific agro-climatic conditions of the middle Gangetic plains. The present study was therefore undertaken to evaluate the influence of four methods of microbial consortia

application, in combination with four integrated nitrogen management schedules, on the growth, productivity and economic performance of *Kharif* sorghum, with a view to identifying the most agronomically and economically efficient combination for the region.

2. Materials and Methods

2.1 Experimental site and period

The field experiment was conducted during *Kharif* 2024 and *Kharif* 2025 at the Research Farm of Naini Agricultural Institute, Faculty of Agriculture, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj-211007 (U.P.), India. The experimental site is located at approximately 25.4°N latitude and 81.8°E longitude at an altitude of about 98 m above mean sea level, representing the subtropical, sub-humid agro-climatic conditions of the middle Gangetic plains.

2.2 Soil characteristics

The pre-experimental soil of the experimental site was analyzed for its physico-chemical properties (0-15 cm depth); the soil was neutral in reaction, non-saline, low in organic carbon and available nitrogen, and medium in available phosphorus, potassium and zinc in both years (Table 1).

Table 1: Pre-experimental soil physico-chemical characteristics (0-15 cm depth)

Soil Characteristic	Method Used	2024	2025
Soil pH (1:2 soil water)	Glass electrode pH meter (Jackson, 1973) ^[3]	6.8	6.9
Electrical conductivity (dS m ⁻¹)	EC meter	0.20	0.21
Organic carbon (%)	Walkley and Black (1934) ^[12]	0.41	0.43
Available N (kg ha ⁻¹)	Subbiah and Asija (1956) ^[10]	220.7	221.4
Available P (kg ha ⁻¹)	Olsen <i>et al.</i> (1954) ^[8]	11.85	12.61
Exchangeable K (kg ha ⁻¹)	Flame photometer (Jackson, 1958) ^[2]	236.75	235.2
Available Zn (mg kg ⁻¹)	DTPA extractant, AAS (Lindsay and Norvell, 1978) ^[6]	0.65	0.59

2.3 Experimental design and treatments

The experiment was laid out in a Randomized Block Design (RBD) with 16 treatment combinations and 3 replications, giving a total of 48 plots. Each plot measured 3 m × 3 m (9 m²). The gross experimental area was 607.6 m², and the net experimental area was 432 m². The sorghum variety Amarnath 2000 was sown at a seed rate of 12 kg ha⁻¹ on 28 June in both seasons. The recommended dose of fertilizer was 80-40-40 kg N-P-K ha⁻¹.

The 16 treatment combinations consisted of a factorial combination of four microbial consortia application methods (Factor A) and four integrated nitrogen management levels (Factor B), as detailed below:

Factor A - Methods of Microbial Consortia Application: A1, Seed treatment @ 30 g kg⁻¹ seed; A2, Soil application @ 2.5 kg/50 kg FYM; A3, Seed treatment + soil application (combined); A4, No consortia (control).

Factor B - Integrated Nitrogen Management: B1, 100% N through urea; B2, 50% N through urea + 50% N through FYM; B3, 50% N through urea + 50% N through vermicompost (VC); B4, 50% N through urea + 25% N through FYM + 25% N through VC.

2.4 Crop management

Pre-sowing irrigation was applied on 21 June, followed by ploughing, harrowing and levelling on 23 June. The microbial consortia for soil application were mixed with

FYM (2.5 kg consortia/50 kg FYM) on 27 June. Seed treatment was carried out on the day of sowing (28 June). Full doses of phosphorus and potassium were applied as basal doses, while nitrogen was applied in two splits—50% as basal and 50% as top dressing at 30 DAS. Thinning and gap filling were done at 10 DAS. Irrigation was applied at 21, 85 and 100 DAS. The crop was harvested at 120 DAS (26 October) in both years.

2.5 Observations recorded

Growth parameters, plant height (cm), dry weight (g plant⁻¹), leaf area index (LAI), crop growth rate (CGR, g m⁻² day⁻¹) and relative growth rate (RGR, g g⁻¹ day⁻¹)—were recorded at 25, 50, 75 and 100 DAS. Post-harvest observations included length of head (cm), number of grains per head, test weight (g), grain yield (kg ha⁻¹), stover yield (kg ha⁻¹) and harvest index (%). Economics were computed in terms of cost of cultivation, gross returns, net returns and benefit-cost (B:C) ratio. Post-harvest soil samples (0-15 cm depth) were analyzed for pH, EC, available nitrogen (Subbiah and Asija, 1956) ^[10] and organic carbon (Walkley and Black, 1934) ^[12].

2.6 Statistical analysis

Data were analyzed statistically using an analysis of variance (ANOVA) appropriate for RBD. The significance of treatment differences was tested at the p = 0.05

probability level. Critical differences (CD) were calculated wherever the F-test was significant. Pooled analysis was performed for the two seasons (2024 and 2025). To facilitate interpretation of the overall treatment effects, pooled values presented in the tables were computed as the arithmetic mean of the two years. These pooled means are descriptive averages and were not subjected to a formal combined analysis of variance.

3. Results and Discussion

3.1 Plant Height

Plant height at 75 and 100 DAS (pooled over 2024 and 2025) was significantly influenced by the different combinations of microbial consortia and integrated nitrogen management (Table 1). Among the treatments, the combined seed treatment and soil application of microbial consortia along with 50% nitrogen through urea + 25% nitrogen through farmyard manure (FYM) + 25% nitrogen through vermicompost (VC) (T12) recorded the maximum plant height of 190.44 cm at 75 DAS and 239.16 cm at 100 DAS, which was significantly superior to all other treatments. This was closely followed by T11 (188.98 and 229.17 cm) and T10 (185.99 and 227.49 cm), indicating that the combined application of microbial consortia with integrated organic and inorganic nitrogen sources consistently enhanced vegetative growth. In contrast, the lowest plant height was observed under the no-consortia treatment receiving 100% nitrogen through urea (T13), recording 145.50 cm and 199.08 cm at 75 and 100 DAS, respectively. The gradual increase in plant height from the no-consortia treatments (T13-T16) to seed treatment alone (T1-T4), soil application alone (T5-T8), and finally the combined seed and soil application treatments (T9-T12) clearly demonstrates the cumulative positive effect of microbial inoculation integrated with balanced nitrogen management on crop growth.

The superior plant height observed under T12 may be attributed to the synergistic interaction between microbial consortia and integrated nutrient sources, which enhanced nutrient availability, stimulated root proliferation, and improved rhizosphere microbial activity. Microbial inoculants facilitate nutrient solubilization, biological nitrogen fixation, and the production of plant growth-promoting substances such as auxins, gibberellins, and cytokinin's, thereby promoting cell division and elongation. Simultaneously, the integration of FYM and vermicompost with urea ensured a continuous and balanced supply of nutrients, improved soil organic carbon, moisture retention, and microbial biomass, thereby creating a favorable environment for sustained plant growth throughout the crop cycle. Conversely, the comparatively lower plant height recorded under the sole urea application without microbial consortia (T13) may be associated with lower nutrient use efficiency, reduced microbial activity, and the absence of a sustained nutrient release pattern. These findings are in agreement with those of Kakde *et al.* (2020) ^[4], who reported enhanced vegetative growth in sorghum following microbial inoculation integrated with organic nutrient sources. Similar improvements in plant height under integrated nitrogen management involving organic amendments and inorganic fertilizers have also been documented by Reddy *et al.* (2023) ^[9] and Kavya *et al.* (2020) ^[5], who attributed these responses to improved nutrient synchronization, enhanced soil biological activity,

and better nutrient uptake throughout the crop growth period.

3.2 Leaf Area Index (LAI)

A similar trend was observed for leaf area index (LAI) at both 75 and 100 DAS (Table 2), where significant differences among treatments were recorded. The combined application of seed treatment and soil application of microbial consortia along with 50% nitrogen through urea + 25% nitrogen through farmyard manure (FYM) + 25% nitrogen through vermicompost (T12) produced the highest LAI values of 4.84 at 75 DAS and 3.92 at 100 DAS. This treatment was statistically superior to all other treatments, indicating that the integrated use of microbial consortia with balanced organic and inorganic nitrogen sources effectively enhanced canopy development. The next highest LAI was recorded under T11 (4.66 and 3.77), followed by T10 (4.46 and 3.60), demonstrating the positive response of sorghum to the combined inoculation of microbial consortia and integrated nutrient management. In contrast, the lowest LAI values (3.45 and 2.77) were observed in the treatment without microbial consortia receiving 100% nitrogen through urea (T13), highlighting the limited effectiveness of sole inorganic nitrogen application in promoting leaf development.

The marked improvement in LAI under T12 can be attributed to the synergistic effects of microbial consortia and integrated nitrogen sources, which enhanced nutrient availability, stimulated root growth, improved rhizosphere microbial activity, and ensured a sustained release of nutrients throughout the crop growth period. The combined application of FYM and vermicompost likely improved soil physical properties, moisture retention, and microbial diversity, while microbial inoculants enhanced nutrient solubilization and biological nitrogen fixation. These processes collectively promoted greater leaf initiation, expansion, and photosynthetic surface area, thereby contributing to superior vegetative growth. Conversely, the absence of microbial inoculation in T13 resulted in comparatively lower nutrient use efficiency and reduced leaf expansion, leading to significantly lower LAI. Similar beneficial effects of integrating microbial consortia with organic and inorganic nutrient sources on canopy development and leaf area have been reported in sorghum and other cereal crops by Kavya *et al.* (2020) ^[5] and Tshering *et al.* (2023) ^[11].

3.3 Dry Weight

Dry matter accumulation exhibited a trend similar to that observed for plant height and leaf area index, with significant differences among the microbial consortia and integrated nitrogen management treatments at both 75 and 100 DAS (Table 3). The combined seed treatment and soil application of microbial consortia supplemented with 50% nitrogen through urea + 25% nitrogen through farmyard manure (FYM) + 25% nitrogen through vermicompost (VC) (T12) produced the highest dry matter accumulation of 100.67 g plant⁻¹ at 75 DAS and 122.94 g plant⁻¹ at 100 DAS, which was significantly superior to all other treatments. This was followed by T11 (93.57 and 116.41 g plant⁻¹) and T10 (88.83 and 114.19 g plant⁻¹), indicating that the combined application of microbial consortia with integrated nutrient management consistently promoted biomass production. In contrast, the lowest dry matter

accumulation was recorded under the no-consortia treatment receiving 100% nitrogen through urea (T13), with values of 70.44 g plant⁻¹ and 100.63 g plant⁻¹ at 75 and 100 DAS, respectively. The progressive increase in dry matter accumulation from the no-consortia treatments to single-method microbial application and finally to the combined seed and soil application treatments demonstrates the beneficial effect of integrating microbial inoculants with balanced nitrogen sources.

The greater biomass accumulation under T12 may be attributed to the synergistic effects of microbial consortia and integrated organic-inorganic nitrogen management, which enhanced nutrient mineralization, improved nutrient uptake efficiency, and stimulated root growth and rhizosphere microbial activity. The balanced combination of urea, FYM, and vermicompost ensured both immediate and sustained nutrient availability throughout the crop growth period, while the microbial consortia enhanced nutrient solubilization and the production of plant growth-promoting substances, resulting in increased photosynthetic efficiency and assimilate production. Improved canopy development, as reflected by higher plant height and leaf area index under the same treatment, likely contributed to greater interception of solar radiation and enhanced dry matter partitioning into vegetative tissues. Conversely, the lower biomass recorded under sole urea application without microbial inoculation (T13) may be associated with comparatively lower nutrient use efficiency, reduced microbial activity, and less favorable soil biological conditions. These findings are in agreement with Kakde *et al.* (2020) [4], who reported enhanced dry matter production in sorghum under microbial consortia integrated with organic nutrient sources. Similar improvements in biomass accumulation through the combined use of microbial inoculants and integrated

nutrient management have also been reported in cereal crops by Negi *et al.* (2022) [7] and Ibarra-Villarreal *et al.* (2023) [1].

3.4 Economics

Cost of cultivation increased progressively with the addition of organic sources (FYM and vermicompost) and with the intensity of microbial consortia application, being lowest under the no-consortia control with 100% urea (T13, INR 36,123.0 ha⁻¹) and highest under the combined consortia application with 50% urea + 50% vermicompost (T7, INR 56,871.5 ha⁻¹) (Table 5). Gross and net returns, however, rose consistently with the combined seed + soil application of consortia, and were maximum under T12 (50% urea + 25% FYM + 25% VC), reflecting the higher biomass and yield attributes recorded for this treatment.

Despite this, the benefit-cost ratio—which weighs returns against the cost incurred—was highest under the combined consortia application with 100% N through urea (T9, B:C = 2.64), followed by the no-consortia control with 100% urea (T13, B:C = 2.12) and the soil-applied consortia with 100% urea (T5, B:C = 2.34). Treatments involving vermicompost and FYM substitution (T2-T4, T6-T8, T10-T12, T14-T16), while agronomically superior in growth parameters, returned comparatively lower B:C ratios because of the added cost of organic inputs relative to the marginal gain in returns. This cost-return trade-off between purely urea-based nitrogen management and organic-substituted integrated nutrient management is consistent with findings that combining biofertilizers with a full or near-full dose of inorganic fertilizer, rather than substituting a large share of nitrogen with costlier organic manures, tends to maximize the benefit-cost ratio even where absolute yields are somewhat lower (Kavya *et al.*, 2020) [5].

Table 1: Influence of Microbial Consortia and Integrated Nitrogen Management on Plant height of Sorghum during Both Years, 2024 and 2025 (Pooled)

Treatment combinations		Plant Height (cm)	
		75 DAS	100 DAS
		Pooled	
T ₁	Seed treatment Consortia (30g/kg) +100% N through Urea	156.94	204.41
T ₂	Seed treatment Consortia (30g/kg) + 50% N through Urea +50% N through FYM	162.26	205.46
T ₃	Seed treatment Consortia (30g/kg) + 50% Urea +50% VC	163.60	207.25
T ₄	Seed treatment Consortia (30g/kg) + 50% N Urea +25% N FYM + 25% N VC	163.96	210.14
T ₅	Soil Application 2.5kg/50kg FYM + 100% Urea	166.03	209.62
T ₆	Soil Application 2.5kg/50kg FYM + 50% Urea +50% FYM	165.09	214.31
T ₇	Soil Application 2.5kg/50kg FYM + 50% Urea +50% VC	171.63	218.63
T ₈	Soil Application 2.5kg/50kg FYM + 50% Urea +25% FYM + 25% VC	170.62	220.19
T ₉	Seed treatment + Soil Application + 100% Urea	174.09	219.02
T ₁₀	Seed treatment + Soil Application + 50% Urea +50% FYM	185.99	227.49
T ₁₁	Seed treatment + Soil Application + 50% Urea +50% VC	188.98	229.17
T ₁₂	Seed treatment + Soil Application + 50% Urea +25% FYM + 25% VC	190.44	239.16
T ₁₃	No Consortia + 100% Urea	145.50	199.08
T ₁₄	No Consortia + 50% Urea +50% FYM	153.46	202.46
T ₁₅	No Consortia + 50% Urea +50% VC	153.21	200.07
T ₁₆	No Consortia + 50% Urea 25% FYM + 25% VC	151.47	201.44
F-test		S	S
SEm (±)		4.31	4.16
CD (p=0.05)		12.08	12.04

Table 2: Influence of Microbial Consortia and Integrated Nitrogen Management on LAI of Sorghum during Both Years, 2024 and 2025 (Pooled)

Treatment combinations		Leaf area Index	
		75 DAS	100 DAS
		Pooled	
T ₁	Seed treatment Consortia (30g/kg) +100% N through Urea	3.65	2.96
T ₂	Seed treatment Consortia (30g/kg) + 50% N through Urea +50% N through FYM	3.73	3.00
T ₃	Seed treatment Consortia (30g/kg) + 50% Urea +50% VC	3.77	3.03
T ₄	Seed treatment Consortia (30g/kg) + 50% N Urea +25% N FYM + 25% N VC	3.84	3.10
T ₅	Soil Application 2.5kg/50kg FYM + 100% Urea	3.91	3.17
T ₆	Soil Application 2.5kg/50kg FYM + 50% Urea +50% FYM	4.00	3.25
T ₇	Soil Application 2.5kg/50kg FYM + 50% Urea +50% VC	4.08	3.29
T ₈	Soil Application 2.5kg/50kg FYM + 50% Urea +25% FYM + 25% VC	4.21	3.37
T ₉	Seed treatment + Soil Application + 100% Urea	4.30	3.44
T ₁₀	Seed treatment + Soil Application + 50% Urea +50% FYM	4.46	3.60
T ₁₁	Seed treatment + Soil Application + 50% Urea +50% VC	4.66	3.77
T ₁₂	Seed treatment + Soil Application + 50% Urea +25% FYM + 25% VC	4.84	3.92
T ₁₃	No Consortia + 100% Urea	3.45	2.77
T ₁₄	No Consortia + 50% Urea +50% FYM	3.54	2.83
T ₁₅	No Consortia + 50% Urea +50% VC	3.56	2.86
T ₁₆	No Consortia + 50% Urea 25% FYM + 25% VC	3.62	2.93
F-test		S	S
SEm (±)		0.11	0.09
CD (p=0.05)		0.44	0.36

Table 3: Influence of Microbial Consortia and Integrated Nitrogen Management on dry weight of Sorghum during Both Years, 2024 and 2025 (Pooled)

Treatment combinations		Dry Weight (g)	
		75 DAS	100 DAS
		Pooled	
T ₁	Seed treatment Consortia (30g/kg) +100% N through Urea	79.17	103.19
T ₂	Seed treatment Consortia (30g/kg) + 50% N through Urea +50% N through FYM	80.80	103.60
T ₃	Seed treatment Consortia (30g/kg) + 50% Urea +50% VC	81.36	103.27
T ₄	Seed treatment Consortia (30g/kg) + 50% N Urea +25% N FYM + 25% N VC	79.95	103.69
T ₅	Soil Application 2.5kg/50kg FYM + 100% Urea	80.55	109.38
T ₆	Soil Application 2.5kg/50kg FYM + 50% Urea +50% FYM	82.52	109.98
T ₇	Soil Application 2.5kg/50kg FYM + 50% Urea +50% VC	83.29	109.23
T ₈	Soil Application 2.5kg/50kg FYM + 50% Urea +25% FYM + 25% VC	84.70	106.95
T ₉	Seed treatment + Soil Application + 100% Urea	87.60	109.62
T ₁₀	Seed treatment + Soil Application + 50% Urea +50% FYM	88.83	114.19
T ₁₁	Seed treatment + Soil Application + 50% Urea +50% VC	93.57	116.41
T ₁₂	Seed treatment + Soil Application + 50% Urea +25% FYM + 25% VC	100.67	122.94
T ₁₃	No Consortia + 100% Urea	70.44	100.63
T ₁₄	No Consortia + 50% Urea +50% FYM	72.56	101.10
T ₁₅	No Consortia + 50% Urea +50% VC	79.92	101.74
T ₁₆	No Consortia + 50% Urea 25% FYM + 25% VC	79.92	102.80
F-test		S	S
SEm (±)		2.01	2.23
CD (p=0.05)		8.21	9.10

Table 4: Influence of Microbial Consortia and Integrated Nitrogen Management on Economics of Sorghum during Both Years, 2024 and 2025 mixed (Pooled)

Treatment's	Economics			
	Cost of cultivation (INR/ha)	Gross returns (INR/ha)	Net returns (INR/ha)	Benefit Cost Ratio (B:C)
	Pooled			
T ₁	36403.3	115928	79524.50	2.18
T ₂	51903.2	116273	64369.90	1.24
T ₃	55903.2	120337	64433.90	1.15
T ₄	53903.2	122816	68912.70	1.27
T ₅	37371.5	124671	87299.20	2.34
T ₆	52871.5	126332	73460.30	1.38
T ₇	56871.5	126504	69632.60	1.22
T ₈	54871.5	132744	77872.40	1.41
T ₉	37383.3	136088	98704.60	2.64
T ₁₀	52883.2	143012	90128.30	1.70
T ₁₁	56883.2	152662	95778.40	1.68
T ₁₂	54883.2	155585	1007020.00	1.83
T ₁₃	36123.0	112835	76712.40	2.12
T ₁₄	51644.8	114324	62679.20	1.21
T ₁₅	55644.8	114596	58951.40	1.05
T ₁₆	53644.8	115634	61988.90	1.15

4. Conclusion

Combined seed treatment and soil application of microbial consortia, integrated with a balanced organic-inorganic nitrogen schedule (50% N through urea + 25% N through FYM + 25% N through vermicompost), consistently produced the greatest plant height, leaf area index and dry matter accumulation in *Kharif* sorghum over both years of study, confirming a synergistic effect of combined microbial inoculation and integrated nutrient management on crop growth. However, from an economic standpoint, combining both consortia application methods with 100% N through urea gave the highest benefit-cost ratio, indicating that the additional cost of organic amendments did not proportionately translate into higher returns per rupee invested. Growers prioritizing maximum vegetative growth and biomass may therefore adopt the combined consortia application with 50% urea + 25% FYM + 25% vermicompost, while those prioritizing economic efficiency may prefer combined consortia application with 100% urea. Further multi-location trials incorporating yield attributes and post-harvest soil health parameters are recommended to validate these findings across seasons and soil types.

Ethical issues

The study did not involve human participants or animal subjects. The authors have no ethical concerns to disclose.

Consent

Not applicable.

Ethical approval

Not applicable, as the study did not involve human participants or animal subjects.

Competing interests

Authors have declared that no competing interests exist.

Authors' contributions

'Amit Kumar' designed the study, conducted the field experiment, performed the statistical analysis, and wrote the first draft of the manuscript. 'Vikram Singh' assisted with the field experiment, managed the data collection, and reviewed the manuscript. All authors read and approved the final manuscript.

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