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Enhancing sorghum productivity through microbial consortia and integrated nitrogen management

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Abstract

A field experiment was conducted during the Kharif seasons of 2024 and 2025 at the Research Farm, Department of Agronomy, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh, to evaluate the effect of microbial consortia and integrated nitrogen management on the productivity of sorghum (*Sorghum bicolor* L. Moench). The experiment was laid out in a Randomized Block Design with 16 treatment combinations comprising four methods of microbial consortia application and four integrated nitrogen management practices, replicated three times. The results revealed significant differences among treatments for yield attributes, grain yield, stover yield and harvest index, whereas test weight remained non-significant. The combined application of seed treatment + soil application of microbial consortia along with 50% nitrogen through urea + 25% through farmyard manure (FYM) + 25% through vermicompost (T₁₂) consistently recorded the highest pooled head length (27.80 cm), grains per head (984.06), grain yield (4457.20 kg ha⁻¹) and stover yield (7289.72 kg ha⁻¹), remaining statistically at par with T₁₁ (seed treatment + soil application + 50% urea + 50% vermicompost). The highest pooled harvest index (37.97%) was recorded under T₁₀, while test weight was not significantly influenced by the treatments. The findings demonstrate that integrating microbial consortia with balanced nitrogen management through inorganic and organic sources enhances nutrient-use efficiency and significantly improves sorghum productivity under the agroclimatic conditions of Prayagraj.

Keywords: Sorghum, microbial consortia, integrated nitrogen management, fym, vermicompost, grain yield

1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a diploid, self-pollinated C4 cereal belonging to the family Poaceae, sub-family Panicoideae, tribe Andropogoneae and genus *Sorghum*, which comprises 24 diverse wild and cultivated species that trace their origin to the wild progenitor *S. bicolor subsp. verticilliflorum* distributed across the north-eastern quadrant of Africa (Ananda et al. 2020) [1]. The crop is botanically classified into five basic races bicolor, guinea, caudatum, kafir and durra on the basis of spikelet and panicle morphology, and it possesses a fibrous root system, a solid pithy stem, and a terminal panicle inflorescence that together confer remarkable tolerance to moisture stress and marginal soil fertility. Its diploid genome (2n = 20) and close phylogenetic relationship with major cereals have made sorghum a model system for genomic and marker-assisted breeding studies aimed at combining high yield potential with resilience to abiotic and biotic stresses (Altaf et al. 2024) [2]. This botanical plasticity, coupled with a C4 photosynthetic pathway, underlies the crop's wide adaptability across the semi-arid tropics and its continuing relevance as a food, feed, fodder and bioenergy crop.

Sorghum ranks among the top five cereal crops of the world after wheat, rice, maize and barley, and is cultivated on roughly 40 to 43 million hectares globally, yielding an average world production in the range of 60 to 63 million tonnes annually, with the United States, Nigeria and Mexico among the leading producers (USDA Foreign Agricultural Service, 2026) [3]. In India, sorghum, popularly known as jowar, is the third most important cereal after rice and wheat among the coarse grains and is cultivated in both the kharif and rabi seasons. As per the third advance estimates for 2023-24, the crop occupied about 47.42 lakh tonnes of production, with kharif sorghum grown predominantly in Rajasthan, Uttar Pradesh, Haryana and Madhya Pradesh, and rabi sorghum concentrated mainly in Maharashtra, Karnataka, Tamil Nadu and Andhra Pradesh (Centre for Agriculture and Rural Development Policy Research [CARD], 2024) [4].

Despite its wide distribution, the national average productivity of sorghum continues to lag behind its genetic potential, largely on account of cultivation on marginal, rainfed and nutrient-deficient soils, underscoring the need for improved agronomic and nutrient management interventions to bridge the existing yield gap.

Within Uttar Pradesh, sorghum occupies a modest but agronomically important niche, with the state ranking among the top producers of jowar in the country and key growing districts including Jhansi, Hamirpur, Fatehpur, Mathura and Prayagraj (Allahabad) contributing to both grain and fodder production (DesiKheti, 2025) ^[5]. In the Prayagraj agroclimatic tract, characterised by sandy loam soils, sub-tropical climate and an average annual rainfall of around 1,100 mm, sorghum is grown chiefly as a multi-cut forage and grain crop during the kharif and zaid seasons and remains an important component of diversified cropping systems practised at research farms of the region. Field investigations carried out at the Crop Research Farm, Department of Agronomy, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, have consistently reported that appropriate nitrogen dose and planting geometry substantially influence plant height, drymatter accumulation and green fodder yield of forage sorghum genotypes such as M P Chari under local sandy loam soil conditions (Chand *et al.* 2023) ^[6]. These location-specific findings highlight that although Prayagraj does not rank among the major sorghum belts of India, its soil and climatic profile offer considerable scope for productivity enhancement through refined planting geometry and nutrient-management practices tailored to the district's resource base.

Nutritionally, sorghum grain is a rich and gluten-free source of dietary energy, containing about 65 to 80 per cent starch, 9 to 13 per cent protein, and appreciable quantities of dietary fibre, B-complex vitamins, phosphorus, magnesium, iron and zinc, along with fatsoluble vitamins such as D, E and K (Tanwar *et al.* 2023) ^[7]. The grain additionally harbours a diverse array of phytochemicals, including phenolic acids, tannins, anthocyanins, phytosterols and policosanols concentrated mainly in the pericarp and bran fractions, which impart pronounced antioxidant, anti-inflammatory and anti-diabetic properties and position sorghum as a promising functional food for addressing lifestyle-related and noncommunicable diseases (Chhikara *et al.* 2018) ^[8]. Its slowly digestible starch and resistant starch fractions further make it suitable for low-glycaemic dietary formulations, while its stover and green fodder serve as valuable livestock feed, reinforcing the crop's dual role in human nutrition and animal husbandry. These attributes, combined with its inherent hardiness, have renewed scientific and industrial interest in sorghum as a climate-smart nutriceal capable of strengthening food and nutritional security in dryland farming systems.

Microbial consortia, comprising compatible combinations of plant growth-promoting rhizobacteria (PGPR) such as *Azotobacter*, *Azospirillum*, phosphate- and potassium-solubilising bacteria and zinc-solubilising isolates, have emerged as an eco-friendly alternative to sole chemical fertilisation for enhancing crop growth and nutrient-use

efficiency. Pot and field evaluations on sorghum have demonstrated that carrier-based dual and multi-strain consortia, when integrated with a reduced dose of inorganic fertiliser and farmyard manure, significantly improve plant height, root and shoot biomass, ear-head characters and grain and stover yield in comparison with either uninoculated or single-strain treatments, owing to synergistic nitrogen fixation, phytohormone production and improved nutrient solubilisation in the rhizosphere (Kavya *et al.* 2020) ^[9]. More recent reviews further emphasise that tailored microbial consortia incorporating PGPR, endophytes and arbuscular mycorrhizal fungi not only enhance nutrient acquisition but also confer improved tolerance to drought and heat stress in sorghum, making microbial-based biofertilisation a key pillar of climate-resilient and sustainable sorghum production systems (Srivastava *et al.* 2025) ^[10].

Nitrogen is the single most limiting nutrient for sorghum growth and yield, and its judicious management through integration of organic, inorganic and biological sources commonly termed integrated nitrogen management (INM) has been shown to sustain productivity while safeguarding soil health. Field studies combining varying nitrogen rates with different irrigation regimes have revealed that an optimum nitrogen level, generally around 144 to 150 kg N per hectare, interacts significantly with soil-moisture status to maximise plant height, leaf-area index, SPAD value and grain yield while minimising nitrate accumulation and the associated risk of nitrogen loss (Wang *et al.* 2024) ^[11]. Complementary evidence from integrated nitrogen trials involving graded substitution of inorganic urea with organic sources such as farmyard manure and castor cake, together with *Azotobacter* and *Azospirillum* inoculation, indicates that partial substitution typically 50 per cent recommended dose of nitrogen (RDN) through urea combined with 50 per cent RDN through organic manure and biofertiliser inoculation consistently outperforms sole chemical fertilisation in terms of growth attributes, grain yield and harvest index, besides improving soil biological health (Inaniyan *et al.* 2026) ^[12]. Such integrated approaches, by synchronising nitrogen availability with crop demand through complementary organic, inorganic and microbial sources, offer a scientifically sound and sustainable pathway for narrowing the yield gap and enhancing the overall productivity of sorghum-based cropping systems.

2. Materials and Methods:

2.1 Experimental site and study area

The field experiment was conducted for two consecutive *Kharif* seasons (2024 and 2025) at the Research Farm of the Department of Agronomy, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Naini, Prayagraj, Uttar Pradesh, India. The experimental site is situated in the sub-tropical belt of the Upper Gangetic Plain agroclimatic zone at approximately 25.38° N latitude and 81.88° E longitude, at an elevation of about 98 m above mean sea level. The region experiences a humid subtropical climate characterised by hot, dry summers, a warm and humid monsoon (July-September), and a cool, dry winter.

Table 1: Pre-experimental soil chemical properties of the experimental site.

Particulars	Value (2024)	Value (2025)	Method used
Soil pH (1:2 soil : water suspension)	7.7	7.6	Glass electrode pH meter (Jackson, 1973) ^[13]
Electrical conductivity (dS m ⁻¹)	0.22	0.21	EC meter
Organic carbon (%)	4.21	4.23	Modified Walkley-Black method (Walkley and Black, 1934) ^[14]
Available (mineralizable) nitrogen (kg ha ⁻¹)	222.7	221.4	Alkaline permanganate method (Subbiah and Asija, 1956) ^[15]
Available phosphorus (kg ha ⁻¹)	12.85	12.61	Olsen's method (Olsen <i>et al.</i> 1954) ^[16]
Exchangeable potassium (kg ha ⁻¹)	235.75	235.2	Flame photometer method (Jackson, 1958)
Available zinc (mg kg ⁻¹)	0.61	0.59	DTPA extractant, estimated on atomic absorption spectrophotometer (Lindsay and Norvell, 1978) ^[17]

Representative soil samples were collected from the plough layer (0-15 cm depth) prior to the layout of the experiment in both years and analysed for chemical properties using standard procedures (Table 1). The soil was slightly alkaline in reaction (pH 7.6-7.7) and nonsaline in nature (EC 0.21-0.22 dS m⁻¹). The

organic carbon status was rated high, while available nitrogen, phosphorus and potassium were medium to high, and available zinc was marginally below the critical level, indicating scope for micronutrient management.

Table 1: Influence of Microbial Consortia and Integrated Nitrogen Management on Length of head and No. of grains/head of Sorghum

	Treatment combinations	Yield Attributes					
		Length of head			No. of grains/head		
		2024	2025	Pooled	2024	2025	Pooled
1	Seed treatment Consortia (30g/kg seed) +100% Urea	22.34	22.91	22.63	768.87	774.31	771.59
2	Seed treatment Consortia (30g/kg seed) + 50% Urea +50% FYM	22.47	23.04	22.75	767.68	773.12	770.40
3	Seed treatment Consortia (30g/kg seed) + 50% Urea +50% VC	22.65	23.22	22.93	769.60	775.04	772.32
4	Seed treatment Consortia (30g/kg seed) + 50% Urea +25% FYM + 25% VC	22.66	23.23	22.95	770.05	775.49	772.77
5	Soil Application 2.5kg/50kg FYM + 100% Urea	23.64	24.21	23.93	777.24	782.68	779.96
6	Soil Application 2.5kg/50kg FYM + 50% Urea +50% FYM	24.37	24.94	24.66	786.93	792.37	789.65
7	Soil Application 2.5kg/50kg FYM + 50% Urea +50% VC	24.20	24.77	24.48	794.21	799.65	796.93
8	Soil Application 2.5kg/50kg FYM + 50% Urea +25% FYM + 25% VC	24.59	25.16	24.88	860.73	866.17	863.45
9	Seed treatment + Soil Application + 100% Urea	24.27	24.84	24.55	891.75	897.19	894.47
10	Seed treatment + Soil Application + 50% Urea +50% FYM	23.91	24.48	24.20	925.72	931.16	928.44
11	Seed treatment + Soil Application + 50% Urea +50% VC	26.11	26.68	26.39	969.36	974.80	972.08
12	Seed treatment + Soil Application + 50% Urea +25% FYM + 25% VC	27.52	28.09	27.80	981.34	986.78	984.06
13	No Consortia + 100% Urea	22.43	23.00	22.71	731.53	736.97	734.25
14	No Consortia + 50% Urea +50% FYM	22.48	23.05	22.77	747.40	752.84	750.12
15	No Consortia + 50% Urea +50% VC	22.65	23.22	22.93	750.27	755.71	752.99
16	No Consortia + 50% Urea +25% FYM + 25% VC	22.85	23.42	23.14	754.09	759.53	756.81
	F-test	S	S	S	S	S	S
	SEm (±)	0.75	0.76	0.53	16.72	17.14	11.85
	CD (p=0.05)	2.16	2.20	1.53	48.31	49.51	34.26

2.2 Experimental design and layout

The experiment was laid out in a Randomized Block Design (RBD) comprising 16 treatment combinations, each replicated thrice, giving a total of 48 plots. *Sorghum* (variety Amarnath 2000) was grown as the test crop at a seed rate of 12 kg ha⁻¹, with a recommended dose of nutrients of 80:40:40 kg N : P₂O₅ : K₂O ha⁻¹. Irrigation and drainage channels were provided between plots to prevent lateral movement of water and nutrients from one treatment to another, and bunds were maintained around each plot.

2.3 Treatment Details

The treatments comprised two factors, viz., (A) method of microbial consortia application and (B) integrated nitrogen management, laid out in all possible combinations.

- **(A) Method of microbial consortia application:** C₁ - seed treatment (30 g consortia kg⁻¹ seed); C₂ - soil application (2.5 kg consortia mixed with 50 kg well-decomposed FYM); C₃ - seed treatment + soil application; and C₄ - control (no consortia).
- **(B) Integrated nitrogen management:** N₁ - 100% N through urea; N₂ - 50% N through FYM + 50% N through urea; N₃ - 50% N through vermicompost (VC) + 50% N through urea; and N₄ - 25% N through FYM+25% N through VC + 50% N through urea, against a recommended

dose of nutrients of 80:40:40 kg N-P-K ha⁻¹. The 16 resultant treatment combinations are listed in Table 4.

2.4 Meteorological conditions during the crop-growing period

The weather during the crop-growing period (June-November) has an important bearing on crop growth, nutrient availability and the activity of the microbial consortia. As station-specific weekly meteorological records for the exact experimental period were not available for compilation, the prevailing weather conditions during the *Kharif* cropping season based on the long-term (normal) climatological data published for the Prayagraj region. Maximum temperature during the crop season ranged from about 29.6 °C to 40.0 °C and declined progressively from June to November, while the minimum temperature ranged from 14.0 °C to 29.0 °C. The bulk of the rainfall (about 80%) was received during July-September, coinciding with the monsoon, after which the crop matured under receding soil moisture and declining relative humidity.

2.5 Statistical analysis

The data recorded for various observations were statistically analysed following the analysis of variance (ANOVA) technique applicable to a Randomized Block Design, as described by Gomez and Gomez (1984), to test the significance of treatment effects at the 5% level of probability. Treatment

means were compared using the standard error of mean (SEM $\pm$) and critical difference (CD at 5%).

3. Result and Discussion:

3.1 Length of head (cm)

2024

The data presented in Table 1 revealed significant variation in length of head among the sixteen treatment combinations during 2024. The treatment T₁₂ (Seed treatment + Soil Application + 50% Urea + 25% FYM + 25% VC) recorded the maximum length of head (27.52 cm), which was statistically at par with T₁₁ (Seed treatment + Soil Application + 50% Urea + 50% VC) (26.11 cm). None of the remaining treatments were statistically comparable with T₁₂. The minimum length of head was recorded under T₁ (Seed treatment Consortia @ 30 g/kg seed + 100% Urea) (22.34 cm), which was statistically at par with T₁₃ (No Consortia + 100% Urea) (22.43 cm) and T₁₄ (No Consortia + 50% Urea + 50% FYM) (22.48 cm).

2025

During 2025, a similar trend was observed (Table 1). T₁₂ again recorded the highest length of head (28.09 cm), statistically at par with T₁₁ (26.68 cm). The lowest length of head was noted under T₁ (22.91 cm), which remained statistically at par with T₁₃ (23.00 cm) and T₁₄ (23.05 cm).

Pooled analysis (2024-2025)

The pooled data (Table 1) confirmed the consistency of the trend across both years. T₁₂ recorded the maximum pooled length of head (27.80 cm), statistically at par with T₁₁ (26.39 cm) (CD at 5% = 1.53). The minimum pooled length of head was recorded under T₁ (22.63 cm), statistically at par with T₁₃ (22.71 cm) and T₁₄ (22.77 cm).

The superiority of the combined seed-cum-soil application of microbial consortia integrated with 50% urea, 25% FYM and 25% VC (T₁₂) over other treatments in length of head can be attributed to the additive and synergistic action of dual inoculation, which ensured continuous rhizosphere and phyllosphere colonisation by the beneficial microbial community throughout the crop growth cycle. Seed treatment establishes an early microbial population around the emerging radicle, while the subsequent soil application replenishes and sustains this population during the vegetative-to-reproductive transition, when nutrient demand for panicle differentiation and elongation is at its peak. The consortia, comprising nitrogen-fixing, phosphate- and potassium-solubilising and plant growth-promoting microorganisms, enhance the mineralisation of native and applied organic nutrients and secrete indole acetic acid, gibberellins and cytokinin-like substances that stimulate cell division and elongation in the meristematic tissue of the developing rachis, thereby increasing the length of the earhead. The partial substitution of inorganic nitrogen with FYM and VC further contributed to a more synchronous nutrient release pattern, since FYM mineralises slowly and provides a steady basal nutrient supply, whereas VC, being partially humified through earthworm gut passage, releases nutrients relatively faster and additionally supplies humic and fulvic acid fractions that improve nutrient and water use efficiency and elicit hormone-like physiological responses in the plant. Similar synergistic improvement in panicle/earhead characters following integration of microbial consortia with organic and inorganic nutrient sources has been reported by Inaniyan *et al.* (2026) ^[12], who observed that integrated nitrogen substitution with FYM combined with microbial inoculants markedly improved yield-attributing characters of sorghum over sole chemical fertilisation. Likewise, Sande *et al.* (2024) ^[18], in a systematic review on integrated nutrient management, concluded that combining vermicompost with inorganic

fertiliser consistently enhanced crop growth and developmental attributes relative to either input applied alone, owing to improved nutrient synchrony and rhizosphere biological activity. In contrast, the lowest length of head under sole seed treatment with 100% urea (T₁) and the no-consortia treatments reflects the absence of a sustained microbial population in the root zone coupled with the well-documented susceptibility of urea-nitrogen to volatilisation and leaching losses under semi-arid conditions, which restricts nitrogen availability during the critical panicle elongation phase and consequently curtails head length.

3.2 Number of grains per head

2024

Data on the number of grains per head (Table 1) revealed that T₁₂ recorded the highest number of grains per head (981.34), which was statistically at par with T₁₁ (969.36) (CD at 5% = 48.31). The lowest number of grains per head was recorded under T₁₃ (731.53), which was statistically at par with T₁₄ (747.40) and T₁₅ (750.27).

2025

During 2025, T₁₂ again recorded the maximum number of grains per head (986.78), statistically at par with T₁₁ (974.80). The minimum value was recorded under T₁₃ (736.97), statistically at par with T₁₄ (752.84) and T₁₅ (755.71).

On pooled basis, T₁₂ recorded the highest number of grains per head (984.06), statistically at par with T₁₁ (972.08) (CD at 5% = 34.26). The lowest pooled value was recorded under T₁₃ (734.25), statistically at par with T₁₄ (750.12), T₁₅ (752.99) and T₁₆ (756.81).

The number of grains per head is largely a function of successful floret initiation, pollination and reduced floret/grain abortion during the anthesis-to-grain-set period, all of which are highly sensitive to the availability of assimilates and nutrients at this critical growth stage. The superior performance of the dual seed-and-soil applied consortia integrated with 50% urea + 25% FYM + 25% VC (T₁₂) can be explained by the sustained enzymatic activity (dehydrogenase, urease and phosphatase) that microbial consortia impart to the rhizosphere, which improves the synchrony between nutrient release from organic sources and the nutrient demand of the crop during panicle development, thereby minimising floret abortion and improving fertilisation efficiency of a greater proportion of florets on the panicle. Sahib *et al.* (2020) ^[19] demonstrated that increasing rhizobacterial species richness in the root zone of sorghum enhanced soil nutrient synergism and plant nutrient assimilation relative to uninoculated or single-strain treatments, supporting the greater nutrient-acquisition efficiency observed under the consortia-based treatments in the present study. Similarly, Inaniyan *et al.* (2026) ^[12] reported that integrated nitrogen management combining urea with organic manures and *Azospirillum* inoculation significantly increased the number of grains per head in sorghum over sole inorganic fertilisation, attributing it to improved nitrogen-use efficiency and prolonged photosynthetic activity of the flag leaf and upper canopy during the grain-filling window. Conversely, the significantly lower grain numbers recorded under the no-consortia sole-urea treatments (T₁₃, T₁₄, T₁₅) are attributable to a mismatch between the pulse-release nature of inorganic urea and crop demand, greater susceptibility of urea nitrogen to volatilisation and leaching under semi-arid kharif conditions, and the absence of a beneficial microbial community to buffer nutrient supply, all of which predispose the crop to source limitation and consequent abortion of the terminal and lower florets on the panicle.

3.3 Grain yield (kg/ha)

The data on grain yield (Table 2) showed that T₁₂ recorded the highest grain yield (4430.43 kg/ha), which was statistically at par with T₁₁ (4340.04 kg/ha) (CD at 5% = 287.09). The lowest

grain yield was recorded under T₁₃ (3129.24 kg/ha), which was statistically at par with T₁₄ (3174.11 kg/ha), T₁₅ (3179.63 kg/ha), T₁₆ (3214.04 kg/ha), T₁ (3224.44 kg/ha) and T₂ (3228.32 kg/ha).

Table 2: Influence of Microbial Consortia and Integrated Nitrogen Management on grains yield and Stover yield of Sorghum

	Treatment combinations	Yield					
		Grain Yield (kg/ha)			Stover Yield (kg/ha)		
		2024	2025	Pooled	2024	2025	Pooled
1	Seed treatment Consortia (30g/kg seed) +100% Urea	3224.44	3272.18	3248.31	6117.91	6201.04	6159.48
2	Seed treatment Consortia (30g/kg seed) + 50% Urea +50% FYM	3228.32	3276.09	3252.20	6193.69	6277.59	6235.64
3	Seed treatment Consortia (30g/kg seed) + 50% Urea +50% VC	3356.53	3404.80	3380.66	6263.56	6347.88	6305.72
4	Seed treatment Consortia (30g/kg seed) + 50% Urea +25% FYM + 25% VC	3426.04	3474.84	3450.44	6391.84	6476.64	6434.24
5	Soil Application 2.5kg/50kg FYM + 100% Urea	3490.14	3539.39	3514.76	6367.02	6451.47	6409.25
6	Soil Application 2.5kg/50kg FYM + 50% Urea +50% FYM	3540.04	3589.79	3564.91	6418.95	6503.88	6461.41
7	Soil Application 2.5kg/50kg FYM + 50% Urea +50% VC	3548.30	3598.08	3573.19	6393.59	6478.60	6436.10
8	Soil Application 2.5kg/50kg FYM + 50% Urea +25% FYM + 25% VC	3754.11	3804.44	3779.28	6412.66	6497.74	6455.20
9	Seed treatment + Soil Application + 100% Urea	3844.08	3894.85	3869.47	6625.26	6710.64	6667.95
10	Seed treatment + Soil Application + 50% Urea +50% FYM	4071.65	4123.41	4097.53	6652.48	6737.96	6695.22
11	Seed treatment + Soil Application + 50% Urea +50% VC	4340.04	4393.54	4366.79	7176.40	7262.25	7219.32
12	Seed treatment + Soil Application + 50% Urea +25% FYM + 25% VC	4430.43	4483.98	4457.20	7246.59	7332.84	7289.72
13	No Consortia + 100% Urea	3129.24	3177.99	3153.61	6033.04	6118.25	6075.65
14	No Consortia + 50% Urea +50% FYM	3174.11	3222.92	3198.52	6080.15	6165.52	6122.84
15	No Consortia + 50% Urea +50% VC	3179.63	3228.47	3204.05	6115.53	6200.89	6158.21
16	No Consortia + 50% Urea 25% FYM + 25% VC	3214.04	3262.91	3238.47	6117.08	6202.47	6159.77
	F-test	S	S	S	S	S	S
	SEm (±)	99.40	101.28	70.88	210.08	213.46	149.16
	CD (p=0.05)	287.09	292.63	204.84	606.76	616.38	431.07

During 2025, T₁₂ again recorded the maximum grain yield (4483.98 kg/ha), statistically at par with T₁₁ (4393.54 kg/ha). The lowest grain yield was recorded under T₁₃ (3177.99 kg/ha), statistically at par with T₁₄ (3222.92 kg/ha), T₁₅ (3228.47 kg/ha), T₁₆ (3262.91 kg/ha), T₁ (3272.18 kg/ha) and T₂ (3276.09 kg/ha).

The pooled data (Table 2) revealed that T₁₂ produced the highest grain yield (4457.20 kg/ha), statistically at par with T₁₁ (4366.79 kg/ha) (CD at 5% = 204.84). The lowest pooled grain yield was recorded under T₁₃ (3153.61 kg/ha), statistically at par with T₁₄ (3198.52 kg/ha), T₁₅ (3204.05 kg/ha), T₁₆ (3238.47 kg/ha), T₁ (3248.31 kg/ha) and T₂ (3252.20 kg/ha).

Grain yield is a cumulative expression of the component yield attributes, namely length of head, number of grains per head and test weight, and its response mirrored the trend recorded for these attributes. The highest grain yield under the combined seed-plus-soil application of microbial consortia with 50% urea supplemented by 25% FYM and 25% VC (T₁₂) may be explained on the principle of nutrient synchrony, wherein the immediate nutrient supply from urea, the slow and steady mineralisation from FYM, and the intermediate release together with humic-substance-mediated physiological stimulation from VC complemented the metabolic activity imparted by the microbial consortia at each successive phenophase, from active vegetative growth through panicle initiation to grain filling. Such synchronisation reduces nutrient loss, improves root proliferation and nutrient use efficiency, and ultimately translates into a greater number of well-filled grains. This finding corroborates Sande *et al.* (2024) ^[18], who reported through a systematic review that the combined application of vermicompost with inorganic fertiliser increased cereal grain yield substantially over sole mineral fertilisation on account of improved soil biological activity and nutrient availability, and Inaniyan *et al.* (2026) ^[12], who observed that integrated nitrogen management with organic manures and microbial inoculants recorded significantly higher grain yield of sorghum compared

with sole chemical fertiliser application. The consistently lowest grain yield recorded under the no-consortia sole-urea treatments (T₁₃-T₁₆) and plain seed-treated, 100% urea treatments (T₁, T₂) can be ascribed to the absence of sustained microbial activity in the rhizosphere, which otherwise assists in nutrient mineralisation, solubilisation and hormonal stimulation, coupled with greater gaseous and leaching losses of urea nitrogen typical of light-textured semi-arid soils, resulting in a lower number of grains per head and reduced overall sink capacity.

3.4 Stover yield (kg/ha)

The data presented in Table 2 indicated that T₁₂ recorded the highest stover yield (7246.59 kg/ha) during 2024, statistically at par with T₁₁ (7176.40 kg/ha) and T₁₀ (Seed treatment + Soil Application + 50% Urea + 50% FYM) (6652.48 kg/ha) (CD at 5% = 606.76). The lowest stover yield was recorded under T₁₃ (6033.04 kg/ha), which was statistically at par with T₁₄ (6080.15 kg/ha), T₁₅ (6115.53 kg/ha), T₁₆ (6117.08 kg/ha) and T₁ (6117.91 kg/ha).

The data on harvest index (Table 3) showed that T₁₀ (Seed treatment + Soil Application + 50% Urea + 50% FYM) recorded the highest harvest index (37.97%) during 2024, which was statistically at par with T₁₂ (37.94%) and T₁₁ (37.69%) (CD at 5% = 1.39). The lowest harvest index was recorded under T₁₃ (34.15%), which was statistically at par with T₁₅ (34.21%), T₂ (34.26%), T₁₄ (34.30%), T₁₆ (34.44%) and T₁ (34.51%).

During 2025, T₁₂ recorded the maximum stover yield (7332.84 kg/ha), statistically at par with T₁₁ (7262.25 kg/ha) and T₁₀ (6737.96 kg/ha) (CD at 5% = 616.38). The lowest stover yield was recorded under T₁₃ (6118.25 kg/ha), statistically at par with T₁₄ (6165.52 kg/ha), T₁₅ (6200.89 kg/ha), T₁₆ (6202.47 kg/ha) and T₁ (6201.04 kg/ha).

During 2025, T₁₀ again recorded the highest harvest index (37.96%), statistically at par with T₁₂ (37.95%) and T₁₁

(37.69%) (CD at 5% = 1.42). The lowest harvest index was recorded under T₁₃ (34.19%), statistically at par with T₁₅ (34.24%), T₂ (34.29%), T₁₄ (34.33%), T₁₆ (34.47%) and T₁ (34.54%).

The pooled data (Table 2) showed that T₁₂ recorded the highest stover yield (7289.72 kg/ha), statistically at par with T₁₁ (7219.32 kg/ha) (CD at 5%=431.07). The lowest pooled stover yield was recorded under T₁₃ (6075.65 kg/ha), statistically at par with T₁₄ (6122.84 kg/ha), T₁₅ (6158.21 kg/ha), T₁₆ (6159.77 kg/ha) and T₁ (6159.48 kg/ha).

Stover yield is primarily a reflection of total vegetative biomass accumulation, which depends on plant height, stem girth, leaf area duration and the efficiency of dry matter production during the vegetative and early reproductive phases.

The higher stover yield recorded under the dual seed-and-soil-applied microbial consortia treatments integrated with organic manures (T₁₀, T₁₁, T₁₂) can be attributed to enhanced root proliferation and rhizosphere volume explored, resulting from improved root hair development and lateral root branching induced by microbial phytohormones, which in turn improved water and nutrient absorption and supported a longer photosynthetically active canopy duration. The incorporation of FYM and VC further improved soil physical properties such as aggregate stability, porosity and moisture-holding capacity, creating a more favourable rhizospheric environment for continued vegetative growth. Kugedera *et al.* (2022) [20] similarly reported that integration of organic biomass sources

with mineral fertiliser improved rainwater-use efficiency and biomass accumulation in sorghum under semi-arid rainfed conditions, while Sande *et al.* (2024) [18] noted that vermicompost-based integrated nutrient management enhances soil organic carbon and microbial biomass carbon, both of which are closely linked with greater vegetative growth and stover accumulation in cereals. The comparatively lower stover yield under the no-consortia, sole-urea treatments reflects restricted root development and shorter canopy duration arising from erratic and often insufficient nitrogen availability, compounded by the absence of the soil-structural and biological benefits conferred by organic manures and microbial inoculation.

3.5 Test weight (g)

2024, 2025 and pooled analysis

The data presented in Table 3 revealed that the effect of microbial consortia and integrated nitrogen management on test weight was statistically non-significant (F-test: NS) during 2024, 2025 as well as on pooled basis. Numerically, the highest test weight was recorded under T₁₂ (30.47 g in 2024, 30.81 g in 2025 and 30.64 g pooled), while the lowest was recorded under T₁₄ (27.00 g in 2024, 27.34 g in 2025 and 27.17 g pooled). Since the F-test was non-significant in all three data sets, the treatments could not be statistically differentiated, and no critical difference (CD) value could be computed.

Table 3: Influence of Microbial Consortia and Integrated Nitrogen Management on Test Weight and Harvest Index of Sorghum

	Treatment combinations	Yield					
		Test Weight			Harvest Index		
		2024	2025	Pooled	2024	2025	Pooled
1	Seed treatment Consortia (30g/kg seed) +100% Urea	28.22	28.56	28.39	34.51	34.54	34.52
2	Seed treatment Consortia (30g/kg seed) + 50% Urea +50% FYM	28.04	28.38	28.21	34.26	34.29	34.27
3	Seed treatment Consortia (30g/kg seed) + 50% Urea +50% VC	28.00	28.34	28.17	34.89	34.91	34.90
4	Seed treatment Consortia (30g/kg seed) + 50% Urea +25% FYM + 25% VC	29.66	30.00	29.83	34.90	34.92	34.91
5	Soil Application 2.5kg/50kg FYM + 100% Urea	29.95	30.29	30.12	35.41	35.43	35.42
6	Soil Application 2.5kg/50kg FYM + 50% Urea +50% FYM	30.00	30.34	30.17	35.55	35.56	35.55
7	Soil Application 2.5kg/50kg FYM + 50% Urea +50% VC	29.54	29.88	29.71	35.69	35.71	35.70
8	Soil Application 2.5kg/50kg FYM + 50% Urea +25% FYM + 25% VC	28.06	28.40	28.23	36.93	36.93	36.93
9	Seed treatment + Soil Application + 100% Urea	29.77	30.11	29.94	36.72	36.72	36.72
10	Seed treatment + Soil Application + 50% Urea +50% FYM	29.33	29.67	29.50	37.97	37.96	37.97
11	Seed treatment + Soil Application + 50% Urea +50% VC	29.50	29.84	29.67	37.69	37.69	37.69
12	Seed treatment + Soil Application + 50% Urea +25% FYM + 25% VC	30.47	30.81	30.64	37.94	37.95	37.95
13	No Consortia + 100% Urea	28.31	28.65	28.48	34.15	34.19	34.17
14	No Consortia + 50% Urea +50% FYM	27.00	27.34	27.17	34.30	34.33	34.31
15	No Consortia + 50% Urea +50% VC	28.04	28.38	28.21	34.21	34.24	34.23
16	No Consortia + 50% Urea 25% FYM + 25% VC	28.00	28.34	28.17	34.44	34.47	34.45
	F-test	NS	NS	NS	S	S	S
	SEm (±)	0.72	0.73	0.51	0.48	0.49	0.34
	CD (p=0.05)	-	-	-	1.39	1.42	0.98

4. Discussion

Test weight, being largely an expression of grain density, endosperm compactness and pericarp thickness, is a relatively conservative trait that is under stronger genetic control and is comparatively less plastic to short-term variation in nutrient management compared with attributes such as the number of grains per head. The non-significant response observed in the present study suggests that, irrespective of the nutrient source or microbial inoculation regime, the assimilate supply during the grain-filling phase was adequate across all sixteen treatments to permit near-complete grain filling, so that any additional benefit accruing from microbial consortia and organic nutrient sources was channelled predominantly into

increasing the number of grains formed (sink number) rather than into further augmenting the weight of individual grains (sink size), a compensatory source-sink relationship frequently observed in cereals under favourable growing conditions. This observation is broadly in agreement with Biswas (2024) [21], who noted in a comprehensive review of PGPR-based bioinoculants that while microbial consortia consistently improve nutrient acquisition and yield-contributing characters, their influence on grain density-related traits such as test weight is often marginal and genotype-dependent. Kugedera *et al.* (2022) [20] likewise reported that in rainfed sorghum, treatment-induced gains in yield were driven mainly by improvements in panicle and grain-number-related traits rather than by test

weight, which remained relatively stable across nutrient management regimes. The slightly higher numerical test weight under the fully integrated consortia treatments may still be agronomically meaningful, reflecting marginally improved grain filling associated with prolonged stay-green duration, even though the difference did not attain statistical significance at the given level of replication.

5. Harvest index (%)

The pooled data (Table 3) confirmed T₁₀ as the superior treatment for harvest index (37.97%), statistically at par with T₁₂ (37.95%) and T₁₁ (37.69%) (CD at 5% = 0.98). The lowest pooled harvest index was recorded under T₁₃ (34.17%), statistically at par with T₁₅ (34.23%), T₂ (34.27%), T₁₄ (34.31%), T₁₆ (34.45%) and T₁ (34.52%).

Harvest index represents the efficiency of partitioning of total dry matter towards economic (grain) yield and is governed by the source-sink balance established during the reproductive and grain-filling phases. It is noteworthy that T₁₀, involving a 1:1 substitution of the recommended urea dose with FYM under the dual consortia application, recorded the highest harvest index even though its absolute grain and stover yields were marginally lower than those of T₁₁ and T₁₂, indicating a more favourable partitioning efficiency rather than sheer biomass superiority. This may be explained by the moderating effect of FYM on the carbon-to-nitrogen ratio of the rhizosphere, which tempers excessive vegetative luxuriance that is typically promoted by higher doses of readily available inorganic nitrogen, thereby favouring a proportionately greater allocation of photosynthates towards the developing grains rather than towards additional vegetative tissue. Microbial consortia further reinforce this balance by improving phosphorus and potassium availability, both of which are critical for phloem loading and translocation of photosynthates to the grain during the grain-filling period. These results are consistent with Sapkota *et al.* (2025)^[22], who reported that integrated nutrient management combining organic and inorganic nitrogen sources produced the highest harvest index in cereals relative to either sole organic or sole inorganic nutrition, and with Sande *et al.* (2024)^[18], who attributed improved harvest index under integrated nutrient management to better source-sink coordination arising from balanced and sustained nutrient availability throughout the crop cycle. The lowest harvest index recorded under the noconsortia sole-urea treatments (T₁₃ and related treatments) reflects a nutrient supply pattern skewed towards early vegetative growth with limited residual nitrogen available for translocation during grain filling, resulting in proportionately greater stover accumulation relative to grain yield and, consequently, a lower harvest index.

6. Conclusion

The study demonstrated that integrating microbial consortia with inorganic and organic nitrogen sources significantly improved sorghum productivity. Among all treatments, T₁₂ (Seed treatment + Soil Application + 50% Urea + 25% FYM + 25% Vermicompost) consistently produced the highest yield attributes, grain yield, and stover yield, while remaining statistically at par with T₁₁. Test weight was not significantly influenced by the treatments. Overall, integrated nutrient management involving microbial consortia with partial substitution of urea by FYM and vermicompost proved to be an effective and sustainable strategy for enhancing sorghum yield.

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8. References

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