Influence of Biofertilizer-Inoculated Spent Mushroom Substrate Soil Amendments on Seed Germination and Early Seedling Development of Sorghum bicolor, Pennisetum glaucum, and Sesamum indicum

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Abstract
The mushroom cultivation industry generates enormous quantities of spent mushroom substrate (SMS), a lignocellulosic by-product that poses significant environmental challenges when improperly disposed of. Despite being considered agricultural waste, SMS contains considerable amounts of organic matter, essential nutrients, microbial biomass, and partially degraded lignocellulosic materials that can be reutilized for sustainable agricultural production. The present study was undertaken to evaluate the potential of biofertilizer-enriched SMS as a soil amendment for improving seed germination, seedling vigour, and growth performance of sorghum (Sorghum bicolor), pearl millet (Pennisetum glaucum) and sesame (Sesamum indicum). Spent mushroom substrate was collected from mushroom waste disposal sites in Kurnool, Andhra Pradesh, and subjected to physicochemical analysis. Beneficial microorganisms including phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), Azospirillum, and Trichoderma spp. were isolated and utilized for biodegradation and enrichment of SMS. The enriched substrate was incorporated into soil at different treatment levels and evaluated through pot experiments. Germination percentage, seedling vigour index, chlorophyll content, root growth, and shoot growth were monitored at regular intervals. Results indicated that microbial enrichment significantly enhanced the agronomic value of SMS by accelerating decomposition and increasing nutrient availability. Germination percentage increased progressively across all treatments, reaching near-complete germination by the fifteenth day. Enhanced seedling vigour, greater chlorophyll content, and improved root and shoot growth were observed in SMS-treated plants compared to untreated controls. The improvement in crop performance was attributed to enhanced nutrient availability, improved soil structure, increased microbial activity, and better moisture retention. The findings demonstrate that biofertilizer-enriched SMS can serve as a sustainable alternative to conventional fertilizers while simultaneously addressing the environmental challenge of mushroom waste disposal. The study highlights the potential of converting agricultural waste into value-added biofertilizer products that contribute to soil health improvement, sustainable crop production, and circular bioeconomy development.

Keywords: Spent mushroom substrate, biofertilizers, phosphate-solubilizing bacteria,potassium-solubilizing bacteria, Azospirillum, Trichoderma, soil fertility,sustainable agriculture, seed germination.

1. Introduction
Agriculture remains the backbone of food security and economic development in many countries, particularly in developing nations where a substantial proportion of the population depends directly or indirectly on farming activities. However, increasing agricultural productivity while maintaining environmental sustainability has become one of the most pressing challenges of the twenty-first century. The intensive use of chemical fertilizers and pesticides has undoubtedly increased crop yields over the past several decades, but their prolonged and indiscriminate application has resulted in soil degradation, nutrient imbalance, environmental pollution, and declining soil microbial diversity. Consequently, there is an increasing demand for sustainable alternatives capable of improving soil fertility and crop productivity while minimizing adverse environmental impacts (Shahwar *et al*., 2023).

Among various sustainable agricultural approaches, the utilization of organic wastes as biofertilizers and soil amendments has gained significant attention. Agricultural and agro-industrial residues constitute a major source of organic matter that can be transformed into valuable agricultural inputs through appropriate biological processes. One such residue receiving considerable research attention is spent mushroom substrate (SMS), the residual material left after mushroom cultivation. The rapid growth of the mushroom industry worldwide has resulted in the generation of enormous quantities of SMS, creating disposal and environmental management challenges (Carpio *et al*., 2023).

Mushroom cultivation involves the growth of edible fungi on various lignocellulosic substrates such as paddy straw, wheat straw, sugarcane bagasse, sawdust, corn cobs, poultry manure, and other agricultural residues. During cultivation, fungal mycelia secrete extracellular enzymes including cellulases, hemi-cellulases, ligninase and oxidases that partially degrade these substrates for nutrient acquisition. Following mushroom harvest, a substantial quantity of partially decomposed substrate remains as waste. This material, commonly known as spent mushroom substrate, contains residual organic matter, fungal biomass, nutrients, enzymes, and beneficial microorganisms that can be exploited for agricultural purposes (Medina *et al*., 2009).

Globally, mushroom production exceeds 40 million tonnes annually, resulting in the generation of several times more SMS than harvested mushrooms. It is estimated that approximately five kilograms of SMS are produced for every kilogram of mushrooms harvested (Carpio *et al*., 2023). Improper disposal of this waste creates serious environmental concerns, including greenhouse gas emissions, nutrient leaching, groundwater contamination, odor generation, and proliferation of pathogenic microorganisms. Consequently, the development of sustainable utilization strategies for SMS has become increasingly important.

The physicochemical composition of SMS makes it a valuable resource for agricultural applications. SMS generally contains high concentrations of organic matter, nitrogen, phosphorus, potassium, calcium, magnesium and micronutrients essential for plant growth (Mwangi *et al*., 2024)Additionally, the organic matter present in SMS contributes to improved soil structure, enhanced water-holding capacity, increased cation exchange capacity, and stimulation of beneficial microbial populations. These properties make SMS a promising candidate for use as an organic fertilizer, soil conditioner, compost amendment, and biofertilizer carrier.

Several studies have demonstrated positive effects of SMS application on soil quality and crop productivity. Medina *et al*. (2009) reported significant improvements in soil physical properties following SMS incorporation, including increased porosity, reduced bulk density, and enhanced water retention. Similarly, (Khan, 2018) observed increased soil nitrogen availability and improved crop growth after application of composted mushroom residues. SMS has also been reported to enhance microbial activity, promote nutrient cycling, and suppress certain soil-borne plant pathogens (Zhu *et al*., 2013).
Despite these advantages, direct application of fresh SMS to agricultural fields may not always be beneficial. Fresh SMS often contains high concentrations of lignocellulosic compounds, elevated salt levels, and unstable organic matter that may temporarily immobilize nutrients or negatively affect plant growth. Furthermore, incomplete decomposition can result in nitrogen immobilization and reduced nutrient availability during early crop growth stages. Therefore, biological stabilization and enrichment of SMS before field application are considered essential for maximizing its agricultural value (Velusami *et al*., 2021).

Biofertilizers represent one of the most promising approaches for enhancing the agronomic potential of SMS. Biofertilizers are formulations containing living microorganisms that improve nutrient availability and promote plant growth through various biological mechanisms. These microorganisms include nitrogen-fixing bacteria, phosphate-solubilizing bacteria, potassium-solubilizing bacteria, plant growth-promoting rhizobacteria, and beneficial fungi. When introduced into organic substrates such as SMS, these microorganisms accelerate decomposition, enhance nutrient mineralization, and improve the quality of the final compost product (Wang *et al*., 2025).

Phosphate-solubilizing bacteria play a crucial role in converting insoluble forms of phosphorus into plant-available forms through the production of organic acids and phosphatase enzymes. Phosphorus is an essential nutrient required for energy transfer, root development, nucleic acid synthesis, and cell division. Although soils often contain significant quantities of total phosphorus, much of it remains unavailable to plants due to fixation in insoluble mineral complexes. The activity of phosphate-solubilizing bacteria therefore contributes significantly to improved phosphorus nutrition and plant growth (Haijie Li etal., 2023).

Similarly, potassium-solubilizing bacteria enhance the availability of potassium by releasing organic acids capable of dissolving potassium-bearing minerals. Potassium is involved in enzyme activation, osmoregulation, photosynthesis, protein synthesis, and stress tolerance. Enhanced potassium availability contributes to improved plant growth, drought resistance, and crop yield.

Azospirillum species represent another important group of biofertilizers widely recognized for their nitrogen-fixing capabilities and plant growth-promoting effects. In addition to atmospheric nitrogen fixation, *Azospirillum* produces phytohormones such as indole acetic acid, gibberellins, and cytokinins that stimulate root development and enhance nutrient uptake. Numerous studies have demonstrated increased germination, seedling vigour, and crop productivity following inoculation with *Azospirillum* (Xuan Bo*et al*., 2025).

The filamentous fungus *Trichoderma* has also emerged as an important component of biofertilizer formulations. Besides its well-known biocontrol properties, *Trichoderma* contributes to decomposition of organic matter, nutrient cycling, root colonization, and plant growth promotion. The fungus secretes various hydrolytic enzymes capable of degrading complex organic compounds, thereby accelerating compost stabilization and nutrient release (Ariff *et al*., 2019).

The integration of these beneficial microorganisms with SMS offers a promising strategy for transforming agricultural waste into a value-added biofertilizer. Microbial enrichment accelerates decomposition of lignocellulosic materials, reduces composting time, improves nutrient availability, and enhances the biological quality of the final product. Such approaches contribute to circular agriculture by recycling agricultural residues into productive inputs while reducing dependence on chemical fertilizers.

Sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), and sesame (*Sesamum indicum*) are economically important crops cultivated extensively in semi-arid and tropical regions. These crops frequently encounter nutrient limitations and moisture stress due to poor soil fertility and adverse environmental conditions. The development of cost-effective and environmentally sustainable nutrient management strategies is therefore essential for maintaining productivity and ensuring food security.

The present investigation was undertaken to evaluate the potential of biofertilizer-enriched spent mushroom substrate as a sustainable soil amendment for improving germination and growth of sorghum, pearl millet, and sesame. The study specifically aimed to assess the effects of enriched SMS on seed germination, seedling vigour, chlorophyll content, root development, shoot growth, and soil health. Furthermore, the research sought to demonstrate the feasibility of converting mushroom industry waste into a valuable agricultural resource through microbial intervention. The findings are expected to contribute toward sustainable waste management, enhanced soil fertility, and environmentally friendly agricultural production systems.

2.METHODOLOGY

2.1 Experimental Design and Treatments

The experiment was designed to assess the effect of biofertilizer-enriched spent mushroom substrate (SMS) on the germination and early seedling growth of sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), and sesame (*Sesamum indicum*). Different proportions of SMS and soil were used as growth substrates to determine the most suitable combination for enhancing seed performance and seedling development.Five substrate combinations were evaluated:T1 – 100% SMS; T2 – 75% SMS: 25% Soil; T3 – 50% SMS: 50% Soil; T4 – 25% SMS: 75% Soil; T5 – 100% Soil (Control). Each treatment was maintained in triplicate and observations were recorded on the 6th, 9th, 12th and 15th day after sowing.

2.2 Germination Studies

Seed germination was monitored to evaluate the influence of the different substrate treatments on seed emergence and establishment. Germination observations were recorded at regular intervals to determine the rate, speed, and overall success of germination under each treatment. A fixed number of seeds (27 seeds for sorghum and pearl millet; 54 seeds for sesame) were sown in each replicate. Germinated seeds were counted periodically and used to calculate germination-related parameters.

Germination Percentage (GP)

$$GP = \frac{\text{Number of germinated seeds}}{\text{Total seeds sown}} \times 100$$

2.3 Mean Germination Time (MGT)

Mean Germination Time (MGT) estimates the average time required for seeds to germinate and reflects the speed of the germination process. It is widely used to compare seed vigour among treatments, with lower values indicating faster and more uniform germination. MGT was calculated according to Ellis and Roberts (1981):

$$MGT = \frac{\sum(Dn)}{\sum n}$$

where:

- D = Number of days from sowing
- n = Number of seeds germinated on day D

Lower MGT values indicate faster germination and better seed vigour.

2.4 Daily Germination Number (DXN)

Daily Germination Number (DXN) provides an estimate of the average number of seeds germinating per day during the observation period. This parameter helps evaluate the rate and uniformity of germination under different substrate combinations.

$$DXN = \frac{\text{Total Germinated Seeds}}{\text{Days Taken for Germination}}$$

DXN provides an estimate of germination speed and uniformity.

2.5 Root and Hypocotyl Length

Root and hypocotyl length are important indicators of early seedling growth and establishment. Measuring these parameters provides information on the influence of substrate treatments on the development of below-ground and above-ground seedling structures. Randomly selected seedlings from each treatment were uprooted carefully and washed with distilled water. Root length and hypocotyl length were measured on Days 6, 9, 12 and 15 using a graduated ruler.

2.6 Vigour Index (VI)

The Vigour Index combines germination percentage and seedling length to provide an overall assessment of seedling performance. It is considered a reliable indicator of seed vigour and the potential of seedlings to establish successfully under different growing conditions. Vigour index was calculated according to Abdul-Baki and Anderson (1973):

$$VI = Germination\ Percentage \times Seedling\ Length$$

where seedling length equals root length plus hypocotyl length.

2.7 Chlorophyll Estimation

Chlorophyll content was determined to evaluate the physiological status and photosynthetic potential of seedlings grown under different treatments. Since chlorophyll concentration reflects plant health and nutrient availability, it serves as an important indicator of seedling quality. Total chlorophyll content was estimated using the acetone extraction method (Arnon, 1949). Fresh leaf tissue was homogenized in 80% acetone and absorbance was measured at 645 and 663 nm.

$$Total\ Chlorophyll = 20.2(A_{645}) + 8.02(A_{663})$$

2.8 Statistical Analysis

Statistical analysis was performed to compare the effects of the different substrate treatments on germination and seedling growth parameters. The data obtained from replicated observations were averaged and used to evaluate treatment responses among the three crop species. Data generated from the Excel sheets were averaged across replications. Germination percentage, MGT, DXN, vigour index, root length, hypocotyl length, and chlorophyll content were compared among treatments and crops.

3. RESULTS AND DISCUSSION

3.1 Effect of Biofertilizer-Enriched Spent Mushroom Substrate on Sorghum (*Sorghum bicolor*) seedling Growth Characteristics

The growth of sorghum seedlings was significantly influenced by the proportion of biofertilizer-enriched spent mushroom substrate (SMS) incorporated into the growth medium. Root length increased steadily throughout the observation period, with T4 (25% SMS + 75% Soil) recording the highest root length (6.47 cm) at Day 15, followe`d by T3 (6.15 cm). The control treatment (T5) produced comparatively lower root growth. Similar trends were observed for hypocotyl development, where T2 (11.66 cm), T3 (11.43 cm), and T4 (11.17 cm) recorded superior elongation compared with the remaining treatments (Table 1).

The enhanced root and shoot growth observed under SMS-amended treatments may be attributed to improved nutrient availability and microbial activity within the substrate. The enrichment of SMS with phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), *Azospirillum*, and *Trichoderma* likely promoted nutrient mineralization and phytohormone production. *Azospirillum* species are known to produce indole acetic acid (IAA), gibberellins, and cytokinins that stimulate root elongation and lateral root formation, thereby increasing nutrient uptake efficiency (Xuan Bo*et al*., 2025). Furthermore, SMS improves substrate aeration, porosity, and water-holding capacity, creating favourable conditions for root proliferation (Medina *et al*., 2009). Similar enhancement in seedling growth following mushroom compost application has been reported in several crops, including cereals and horticultural species (Khan, 2018).

The vigour index of sorghum differed significantly among treatments (Figure 1A). The highest vigour index was recorded under T4 (approximately 635), followed by T3 (545) and T5 (530), while T1 showed the lowest value (430). The increase in vigour index reflects improved germination percentage and greater seedling growth under SMS-amended treatments.

Vigour index is considered a reliable indicator of seedling quality and field establishment potential (Abdul-Baki and Anderson, 1973). The superior vigour observed in T4 suggests that moderate SMS incorporation created an optimal environment for germination and early growth. Similar increases in seedling vigour have been reported following the application of mushroom compost and biofertilizer-enriched organic amendments, where enhanced nutrient availability and microbial activity contributed to improved plant establishment (Mwangi *et al*., 2024; Wang *et al*., 2025) (Fig.1A).

Mean germination time (MGT) and daily germination number (DXN) are important indicators of germination speed and uniformity. Sorghum seedlings grown under T4 exhibited the highest DXN values and more synchronized germination compared with other treatments (Figures 1B and 1C). Faster and more uniform germination indicates improved seed metabolic activity and enhanced utilization of stored reserves.

The reduction in germination time observed under SMS-amended treatments may be associated with improved moisture retention and microbial production of growth-promoting substances. During seed imbibition, adequate moisture availability is essential for activating enzymes responsible for reserve mobilization (Bewley *et al*., 2013). Biofertilizer inoculants may further accelerate germination by producing phytohormones that stimulate embryo growth. Similar improvements in germination kinetics have been reported in crops treated with microbial inoculants and organic amendments (Haijie Li etal., 2023i).

Total chlorophyll content increased significantly with SMS incorporation (Figure 1D). The highest chlorophyll concentration was recorded under T4 (0.0071 mg g^{-1}), followed by T3 (0.0061 mg g^{-1}), whereas lower values were observed in T1 and T2.

Chlorophyll concentration is directly related to nitrogen availability and photosynthetic efficiency. The increased chlorophyll content under SMS-amended treatments indicates improved nutrient uptake and enhanced physiological activity. Nitrogen forms a structural component of chlorophyll molecules, while phosphorus contributes to energy transfer processes involved in photosynthesis (Arnon, 1949). Similar increases in chlorophyll concentration following mushroom compost application have been reported by Khan (2018), who attributed the response to improved nutrient availability and microbial activity.

Table 1. Root and Hypocotyl Growth of the millets under Different Treatments

		Sorghum bicolor				**Pennisetum glaucum**				**Sesamum indicum**			
Treatment	Parameter	Day 6	Day 9	Day 12	Day 15	Day 6	Day 9	Day 12	Day 15	Day 6	Day 9	Day 12	Day 15
T1	Average root length (cm)	4.28	4.81	5.00	5.36	3.75	4.25	2.17	1.34	0.01	0.60	2.57	3.45
	Average hypocotyl length(cm)	8.67	10.61	10.79	10.99	5.94	6.68	1.13	2.21	0.03	1.64	2.90	4.30
T2	Average root length(cm)	4.94	4.72	4.89	5.58	6.28	4.07	5.44	4.56	0.01	0.50	2.97	3.31
	Average hypocotyl length(cm)	8.72	11.34	11.55	11.66	6.42	6.65	5.43	6.46	0.03	1.77	3.47	3.73
T3	Average root length(cm)	5.16	5.80	5.97	6.15	5.72	4.84	4.90	6.11	0.01	0.67	3.33	3.68
	Average hypocotyl length(cm)	9.00	11.27	11.47	11.43	7.43	7.91	6.58	8.97	0.02	1.83	3.80	4.17
T4	Average root length(cm)	5.30	6.17	6.37	6.47	4.44	4.79	3.72	5.20	0.01	0.57	3.03	3.57
	Average hypocotyl length(cm)	8.77	10.69	10.88	11.17	6.31	6.67	5.27	7.55	0.02	1.97	4.93	5.30
T5	Average root length(cm)	5.05	5.65	5.93	5.98	3.45	3.62	2.67	3.74	0.01	0.50	3.15	3.36
	Average hypocotyl length(cm)	8.15	9.86	10.10	10.26	5.22	5.66	4.40	6.56	0.02	1.50	3.85	4.15

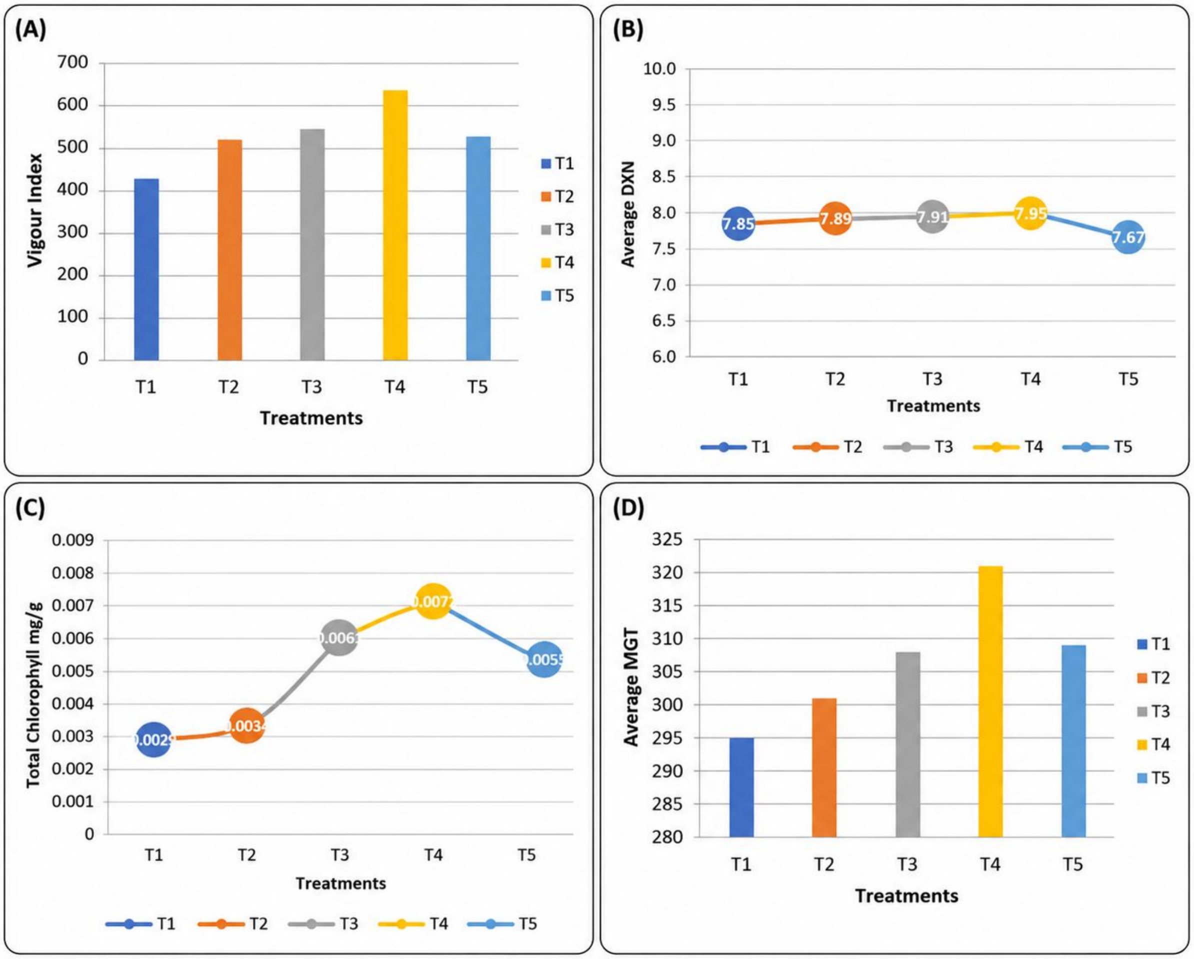

Figure1A: Vigour Index of *Sorghum bicolor* under Different SMS Treatments;1B: Mean Germination Time of *Sorghum bicolor*;1C: Daily Germination Number of *Sorghum bicolor*; 1D: Total Chlorophyll Content of *Sorghum bicolor*

3.2 Effect of Biofertilizer-Enriched SMS on Pearl Millet (*Pennisetum glaucum*) seedling Growth Characteristics

Pearl millet exhibited significant improvements in root and shoot growth under SMS-amended treatments. The highest root length was observed under T3 (6.11 cm), followed by T4 (5.20 cm), whereas T1 recorded the lowest value. Hypocotyl growth followed a similar pattern, with T3 producing the greatest elongation (table 1).

The enhanced seedling growth under T3 suggests that a balanced combination of SMS and soil provided optimum nutrient availability and favourable physical conditions. SMS contains substantial quantities of organic matter that improve soil structure and water retention. Moreover, microbial enrichment enhances nutrient mineralization and phosphorus solubilization, supporting root development and biomass accumulation (Haijie Li etal., 2023). Comparable observations have been reported by Medina *et al*. (2012), who found improved seedling growth and nutrient uptake following incorporation of mushroom compost into agricultural soils.

Pearl millet recorded the highest vigour index under T4, followed by T3 and T2 (Figure 2A). The increase in vigour index indicates that SMS incorporation improved both germination percentage and seedling growth.
The higher vigour values may be explained by the synergistic interaction between organic matter decomposition and microbial inoculation. Organic substrates provide carbon sources that stimulate microbial activity, while biofertilizers enhance nutrient availability. Such interactions create a biologically active rhizosphere that supports seedling establishment (Velusami *et al*., 2021) as shown in the fig.2A.

The germination characteristics of pearl millet improved with SMS incorporation. Treatments T3 and T4 recorded higher DXN values and lower MGT, indicating rapid and synchronized germination. Faster germination is advantageous because it improves seedling competitiveness and reduces vulnerability to environmental stresses during emergence (fig. 2B).

The positive of SMS on germination may result from improved substrate moisture retention and the production of growth-promoting compounds by beneficial microorganisms. Similar improvements in germination performance have been documented in cereals grown with organic amendments and microbial inoculants (Xuan Bo*et al*., 2025).

The highest chlorophyll concentration was observed in T4, followed closely by T3. Increased chlorophyll accumulation indicates enhanced nitrogen uptake and improved photosynthetic activity.

This observation agrees with Zhu *et al*. (2013), who reported that SMS amendments stimulate microbial activity and nutrient cycling, leading to increased chlorophyll synthesis and improved plant productivity.

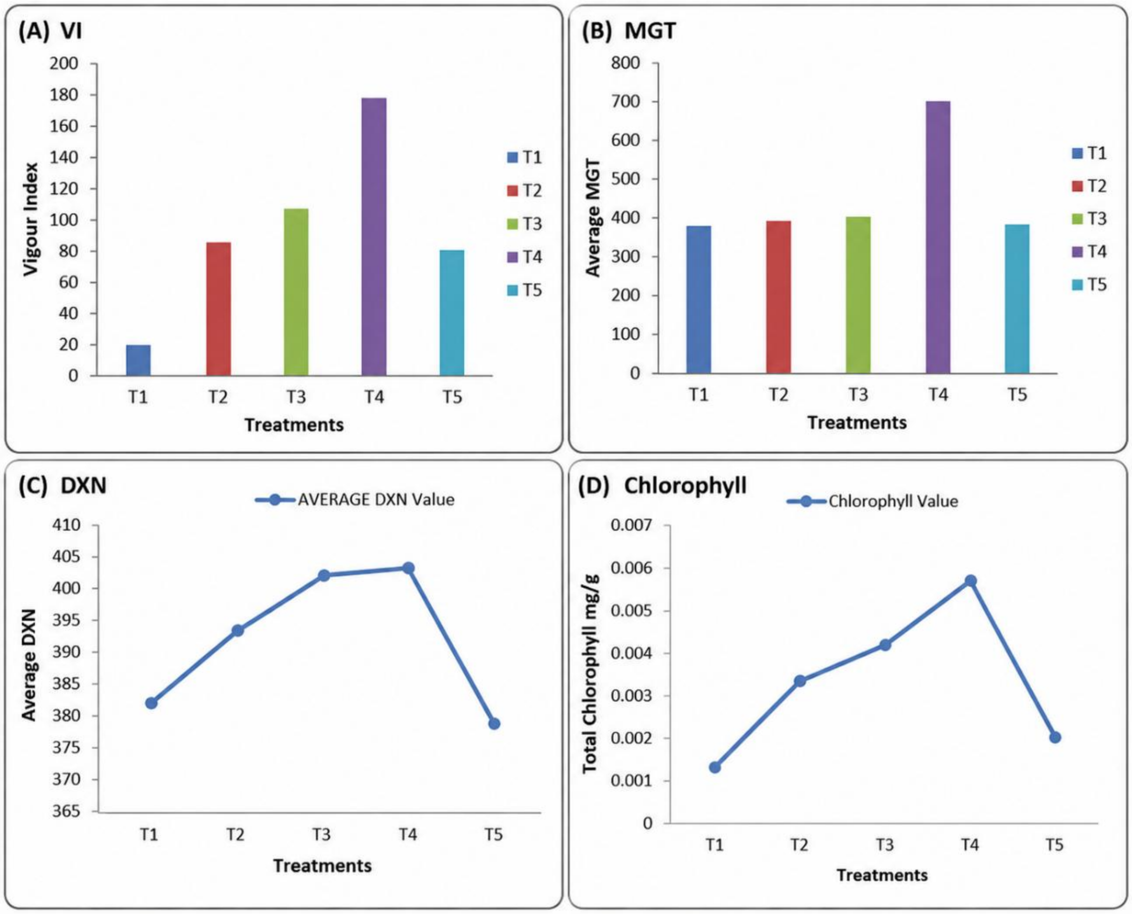

Figure 2A: Vigour Index of *Pennisetum glaucum* under Different SMS Treatments; 2B: Mean Germination Time of *Pennisetum glaucum*; 2C: Daily Germination Number of *Pennisetum glaucum*; 1D: Total Chlorophyll Content of *Pennisetum glaucum*

3.3 Effect of Biofertilizer-Enriched SMS on Sesame (*Sesamum indicum*) on seedling Growth Characteristics

Sesame seedlings responded positively to SMS incorporation, although growth responses were less pronounced than those observed in sorghum and pearl millet. Root length was highest under T3 (3.68 cm), whereas hypocotyl elongation was greatest under T4 (5.30 cm) (table 1).

The comparatively slower growth of sesame may be related to species-specific differences in nutrient requirements and seed reserve utilization. Nevertheless, the superior performance under T3 and T4 suggests that moderate SMS incorporation improved nutrient availability and root-zone conditions. Similar responses have been reported in oilseed crops treated with compost-based amendments (Mwangi *et al*., 2024).

The vigour index increased markedly under SMS-amended treatments, with T4 recording the highest value (approximately 240) compared with T1 (132). The improvement in vigour reflects enhanced germination and seedling growth.

Greater vigour under SMS treatments may be attributed to improved nutrient availability and microbial-mediated growth promotion. Vigorous seedlings generally exhibit higher stress tolerance and better field establishment, ultimately contributing to improved crop productivity (Abdul-Baki and Anderson, 1973).

DXN increased progressively from T1 to T4 and subsequently declined in the control treatment. The higher DXN values observed under T4 indicate rapid and uniform germination. Lower MGT values further support the positive effect of SMS enrichment on seed emergence.

The improved germination characteristics may result from enhanced substrate moisture availability and microbial production of plant growth regulators. Similar findings have been reported for sesame and other oilseed crops grown under organic nutrient management systems (Wang *et al*., 2025).

Chlorophyll content increased significantly with SMS incorporation, reaching maximum values under T4 (0.0093 mg g^{-1}) and T3 (0.0091 mg g^{-1}). Enhanced chlorophyll accumulation suggests improved nitrogen assimilation and photosynthetic efficiency.

The increase may be attributed to biological nitrogen fixation by *Azospirillum* and nutrient mineralization facilitated by *Trichoderma*. Similar increases in chlorophyll concentration following application of biofertilizer-enriched composts have been reported by Khan (2018).

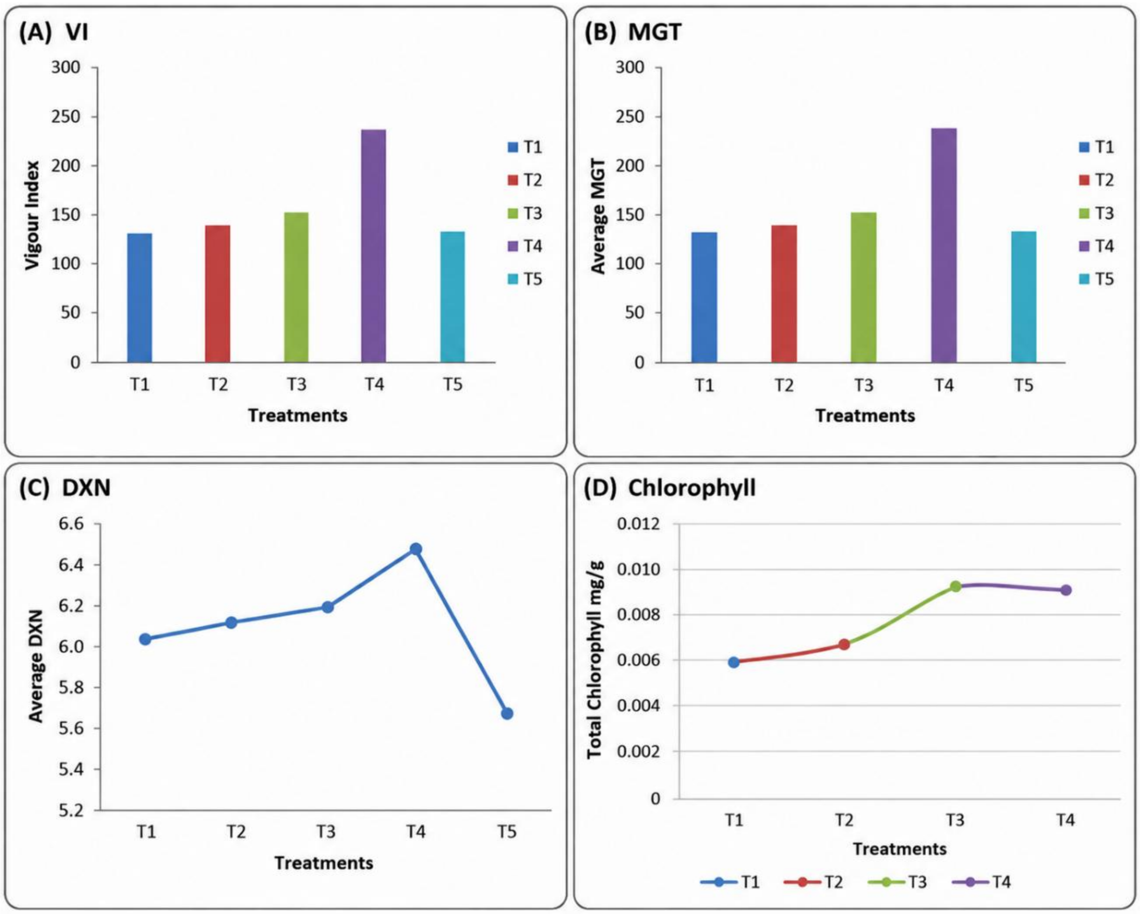

Figure 3A: Vigour Index of *Sesamum indicum* under Different SMS Treatments; 3B: Mean Germination Time of *Sesamum indicum*; 3C: Daily Germination Number of *Sesamum indicum*; 3D: Total Chlorophyll Content of *Sesamum indicum*

4. CONCLUSION

The present investigation demonstrated the potential of biofertilizer-enriched spent mushroom substrate (SMS) as an effective and sustainable soil amendment for improving seed germination and early seedling growth of sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), and sesame (*Sesamum indicum*). Spent mushroom substrate, when enriched with beneficial microorganisms including phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), *Azospirillum* spp., and *Trichoderma* spp., exhibited enhanced agronomic value through accelerated decomposition, improved nutrient mineralization and increasedbiologicalactivity(Haijie Li etal., 2023).

The germination studies revealed that all crops responded positively to SMS incorporation, although the magnitude of response varied among species. Pearl millet exhibited the highest overall germination performance, followed by sorghum and sesame. Germination percentage increased progressively throughout the experimental period and reached maximum levels by the fifteenth day in most treatments. Treatments containing a balanced combination of SMS and soil, particularly T3 (50% SMS + 50% soil) and T4 (25% SMS + 75% soil), consistently recorded superior germination characteristics, indicating that moderate incorporation of SMS provided optimal conditions for seed imbibition, nutrient availability, and seedling establishment.

Seedling vigour, root development, hypocotyl growth, chlorophyll content, and germination kinetics were significantly enhanced under SMS-amended treatments. Improved root proliferation and shoot elongation observed in sorghum, pearl millet, and sesame suggest enhanced nutrient acquisition and physiological activity. Increased chlorophyll accumulation further indicated improved photosynthetic efficiency resulting from greater availability of nitrogen, phosphorus, and potassium released during microbial decomposition of SMS. The beneficial effects observed may be attributed to the synergistic action of biofertilizer microorganisms, which promote nutrient solubilization, biological nitrogen fixation, phytohormone production and organic matter decomposition.

The findings confirm that biofertilizer-enriched SMS can be effectively utilized as a low-cost and environmentally sustainable alternative to conventional soil amendments. In addition to improving crop establishment and seedling performance, the technology offers an efficient strategy for recycling mushroom industry waste into value-added agricultural inputs. Such utilization contributes to improved soil fertility, enhanced microbial diversity, reduced dependence on chemical fertilizers, and promotion of circular bioeconomy principles.

Overall, the study demonstrates that enrichment of spent mushroom substrate with beneficial microorganisms represents a promising approach for sustainable crop production and agricultural waste management. Future studies should focus on field-scale validation, long-term soil health assessment, nutrient dynamics under different agroecological conditions, and the influence of enriched SMS on crop yield and quality parameters under commercial cultivation systems.

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