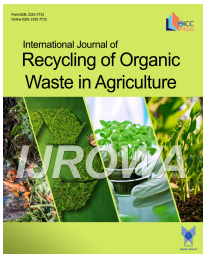

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Application of lignocellulolytic fungal consortium for quality composting of spent mushroom substrate: physicochemical parameters and maturity assessment of the end-products

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Original Research

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Abstract:

Purpose:The inappropriate disposal of agricultural residues including spent mushroom substrate (SMS) after harvesting leads to serious environmental issues. Microbial composting is a widely recognized method for the management of such residues in a sustainable manner. Therefore, the present study aims to examine the efficacy of lignocellulolytic fungal consortium (*Pseudoplagiostoma eucalypti* strain LLF10 and *Purpureocillium lilacinum* strain LLF22) on the composting of SMS.

Method: The experiment consisted of two treatments- T0: only SMS, and T1: SMS + fungal accelerator solution (FAS) + Fungal consortium. The composting process lasted for 42 days and physicochemical parameters were assessed.

Results: The results displayed that the fungal consortium accelerated SMS composting as evidenced by the decrease in the C:N ratio, an increase in macronutrient contents (TN, TK, TP, TCa, TMg), coarseness index (CI), and germination index (GI) of the final compost (T1) over the control (T0). Fourier transform infrared (FTIR) analysis revealed the breakdown of aromatic and organic compounds in the final compost suggesting humification of SMS. Furthermore, the inoculation of the fungal consortium effectively induced a faster rise in temperature and pH.

Conclusion: This study revealed that the lignocellulolytic fungal consortium can be a potential candidate for the bioconversion of agro-waste into high-quality compost for application in sustainable agricultural practices.

Keywords: Fungal consortium; Fungal accelerator solution; Spent mushroom substrate; Coarseness index; Germination index

1. Introduction

Mushroom cultivation is one of the common agricultural practices in India producing around 0.13 million tons (Sharma et al., 2018). Mushrooms are used for food or other industrial uses. Because of their high nutritional value, the demand for the production of mushrooms has been increasing in recent times. They are cultivated using different lignocellulosic substrates such as wheat straw, soybean straw, pea straw, paddy straw, coconut coir pith, cotton waste, and sugarcane bagasse (Maurya et al., 2019). As a consequence, a huge amount of substrate usually called as spent mushroom substrate (SMS) is generated after the cultivation process. These SMS are frequently discarded in the trash, left in the field, or even sometimes burnt out. Such irrational agro-waste management techniques greatly exacerbate environmental deterioration (Werghemmi et al., 2022; Abou Fayssal et al., 2023). The burning of biomass emits greenhouse gases such as CO_2 and CO into the environment which results in pollution and causes health hazards (Das and Deka, 2021). According to reports, one of the primary causes of the world's anthropogenic CH_4 emissions

is organic waste disposal facilities (Powell et al., 2016). Additionally, the careless disposal and dumping of agricultural leftovers after harvest results in the annual release of 2.8 metric tonnes of CH_4, or almost 60 metric tonnes of CO_2 (Cardoen et al., 2015).

As SMS is often underused after harvesting, recycling this substrate into value-added products through composting would be a better strategy for eco-friendly management and utilization. In this regard, microorganisms especially fungi are well known for being the lignocellulolytic enzyme producer which accelerates the degradation of organic matter in the environment (Zhang et al., 2018). The final product of microbial composting is widely recognized for having a variety of advantageous qualities in the soil, including chemical, biological, and physical characteristics that can support sustainable agricultural output (Rastogi et al., 2020; Chang et al., 2021a). Besides, the microbial composting product can enhance the disease-resistant capacity of plants by inducing metabolic compounds and suppressing the various soil-borne pathogens (Chang et al., 2021b). Numerous researchers worldwide have already demonstrated the effectiveness of microbial composting in managing various agricultural residues. For instance, the efficacy of composting agro-wastes employing *Trichoderma harzianum* has been carried out in the mixture of maize-cob, groundnut pods, sawdust, and Guinea grass (Soretire et al., 2022); rice straw (Sarangi et al., 2021); rice straw composting employing *Phanerochaete chrysosporium* (Chen et al., 2019); wheat straw composting using *Aspergillus* strains (Greff et al., 2022), and many others. However, amendments or additives are one of the most important factors that support microbial growth and metabolic activities during the process of composting which subsequently help to achieve quality composting end-products (Ayilara et al., 2020; Chung et al., 2021). Various amendments such as biochar (Jain et al., 2018), zeolite (Chan et al., 2016), bamboo charcoal (Hua et al., 2008), phosphate (Wang et al., 2019), and many more have been reported by several workers, but meager information is available on their role in microbial growth and metabolic activities in composting processes. In the present study, fungal accelerator solution (FAS) was amended to support the fungal growth and metabolic activities that take place during the decomposition process. Nevertheless, the reports on composting of SMS employing fungal strains are revealed to be extremely sparse. Therefore, a perspective on fungal activities in waste conversion technologies is important to provide new insights into the management of agro-waste and sustainable utilization.

Taking into account the aforementioned facts, the current study was proposed to examine the potential of two lignocellulolytic fungal isolates for the conversion of SMS obtained after the cultivation of Oyster mushrooms using citronella bagasse into a high-value compost. The quality of the composting process was assessed based on changes in physiochemical properties, microbial profiles, FTIR analysis, and phytotoxicity test.

2. Materials and methods

Fungal strains

Previously isolated two biocompatible lignocellulolytic fungi-*Pseudoplagiostoma eucalypti* strain LLF10 (OP352678) and *Purpureocillium lilacinum* strain LLF22 (OP315272) were selected for the present study (Mili et al., 2023). The fungi strains were cultivated in Erlenmeyer flasks containing Potato Dextrose Broth (PDB) at 28 ± 2 ºC in a BOD incubator for 6 days.

Preparation of fungal accelerator solution (FAS)

The FAS was prepared with the ripened fruit of banana (*Musa balbisiana* Colla) and jaggery. Briefly, 50 g banana was ground and added to a container containing 500 mL of distilled water and mixed properly. Thereafter, the solution was subjected to the separately prepared 500 mL of jaggery solution (50 g jaggery + 500 mL distilled water) and mixed well. The final solution was sterilized and considered as FAS. The purpose of the addition of FAS in the composting process was to enhance the growth of fungi in the initial stage as both jaggery and banana pulp are good sources of carbohydrates, vitamins, and moisture. This solution acts as a carbon source and therefore can be an alternative to synthetic media and more cost-effective.

Composting setup

The SMS was collected from the mushroom cultivation unit of the Botany Department, Gauhati Unversity, Guwahati, Assam, India. The SMS was a residual remains of citronella bagasse used for the cultivation of Oyster mushrooms (*Pleurotus ostreatus*). The raw material was sun-dried and chopped into a range of $1.0 - 2.0$ cm in size. The composting was carried out in earthen pots with a depth of 25 cm and a radius of 12 cm. The composting experiments consisted of two treatments (T0, and T1). Before, the experimental setup SMS was separated into two parts of 500 g each. One part was moistened with the sterilized FAS up to $60 \pm 5\%$ and left for 30 min for proper absorption. Finally, the moistened SMS was loaded into the composting pot (T1) and the other part (without FAS moistened SMS) was loaded into another pot (T0). After 24 h, 30 mL of each 6-day-old fungal culture (10^7 spores/mL) was inoculated into T1. Neither FAS nor fungal culture was added to the T0 and considered as a control. Polythene sheets were placed over the pots and numerous tiny pores were created to provide enough aeration. The composting pots were kept in the Botanical Garden of the Department and the experiment was extended to 42 days. Besides, the compost medium was kept at a moisture level of $60 \pm 5\%$ by misting it with distilled water as needed. The compost loads were flipped over once per 2 days in the 1st week, once per 4 days in the 2nd to 3rd weeks, and once per 10 days in the 5th and 6th weeks. Samples were collected on days 0, 7, 14, 21, 28, 35, and 42, from three points of the composting piles at different depths and then mixed. The collected compost samples were brought into the laboratory and stored at 4 ºC for analysis.

Physicochemical and FT-IR analysis

For the determination of the physicochemical parameters, the samples-raw material, SMS compost, and control were air-dried. Particle-size distribution and Coarseness index (CI) were evaluated as explained by Gabhane et al. (2012). Samples of air-dried compost were shaken for $2-3$ min on filter mesh with 0.25, 0.5, 1, 2, and 5 mm apertures. Every filter mesh's retained material was weighed. The percentage of particles >1 mm, i.e. the CI was computed based on air-dried weight (Jayasinghe, 2012). The temperature was measured with a soil thermometer inserted in the middle of the composting pile at around 2:00 p.m. every day during the composting period. A digital pH meter (Labrotonics, Model: LT-10) was utilized to measure the pH after a sample and water suspension were prepared in a 1:10 (w/v) ratio. The samples' total organic carbon (TOC) contents were determined using the Walkey and Black titration method. Total nitrogen (TN) content was measured by the micro Kjeldhal method (Bradstreet, 1954). The ratio of C:N of the samples was estimated from the TOC and TN values. The total potassium (TK) was determined by the acid digestion method in a flame photometer (APHA, 1998). The total phosphorus (TP) was measured by following the stannous chloride method (APHA, 1998). The total Ca (TCa) and Mg (TMg) were analyzed by the EDTA titration method (Raij, 1966). The trace elements such as Fe and Mn concentration were measured by Atomic Absorption Spectrophotometer (AAS- PerkinElmer-000) after acid digestion of the samples as described by Hseu (2004). An FTIR spectrophotometer (THERMO SCIENTIFIC) was used to obtain the samples' Fourier transform infrared (FTIR) spectra. After mixing the samples with KBr, they were homogenized in an agate mortar and formed into pellets. Wave numbers for the recorded infrared spectra ranged from 4000 to 500 cm^{-1}.

Analysis of microbial numbers

One (1) gram of each control and treated SMS was weighed and added to a flask containing 100 mL of autoclaved distilled water and shaken for 30 min. Serial dilutions ($10^{-1}-10^{-7}$) were prepared from this initial suspension. Aliquots of 250 μL from dilutions 10^{-5}, 10^{-6}, and 10^{-7} were pipetted into each Nutrient Agar (NA) and Potato Dox Agar (PDA) plate (three replicates) for bacteria and fungi respectively, and spread with a glass spreader gently. In the case of PDA media, streptomycin sulfate (200 μg/L) was added as an antibacterial agent. After sealing the plates with parafilm, they were placed in a Bio-Oxygen Demand (BOD) incubator set to 35 ± 2 °C for bacteria and 28 ± 2 °C for fungi for $1-3$ days and $3-6$ days, respectively. The fungal and bacterial colonies that appeared on plates with dilutions of 10^{-5} and 10^{-7}, respectively, were appropriate for determining a Colony-forming Unit (CFU) and were noted.

Phytotoxicity test

The seeds of *Phaseolus vulgaris* L. (bean) were used in this experiment. First, a total number of 27 seeds were washed and surface sterilized with 70% alcohol and pre-soaked in distilled water for 1 h. For the seed germination test, 100 g of garden soil, T0, and T1 compost products were taken separately in cleaned Petri plates and the plates containing the garden soil were considered as the control. Three seeds were placed in each plate at equidistance and moisture content was maintained by misting them with distilled water for 6 days. The test was conducted in triplicates. After 12 days, the germination index (GI) was computed with the formulas given below (Khatua et al., 2018).

$$\text{RSG} = \frac{\text{Number of seeds germinated in the sample}}{\text{Number of seeds germinated in the control}} \times 100$$

$$\text{RRG} = \frac{\text{Mean root length in the sample}}{\text{Mean root length in the control}} \times 100$$

$$\text{GI} = \frac{\text{RSG} \times \text{RRG}}{100}$$

where, RSG: relative seed germination, RRG: relative root growth, GI: germination index.

Data analysis

All the experiments were done in triplicates ($n = 3$) and the mean and standard deviation (SD) were calculated using Microsoft Office Excel. The analysis of the One-way ANOVA, Pair t-test ($p < 0.05$), and Spearman's correlation was done using SPSS (version: 16.0).

3. Results and discussion

Variations of temperature and pH

Temperature is a crucial factor in the composting process as its variation is linked with the degradation of organic substances and colonization of microorganisms (Deka et al., 2011). The composts exhibited both thermophilic and mature phases during the composting period (Fig. 1). The ambient temperature exhibited between 17 ℃ and 29 ℃. The temperature in the T1 experienced a sharp rise after 6 days and reached above 55 ℃ whereas in T0 the temperature increased very late i.e. after 15 days and reached up to 50 ℃ gradually. The thermophilic phase persisted for 9 days and 5 days in T1 and T0 respectively. The gradual rise of temperature at the initial stage in the T1 as compared to T0 might be possibly due to the addition of FAS which may have supported the growth of inoculated fungi. In many instances, different substrates especially jaggery and banana

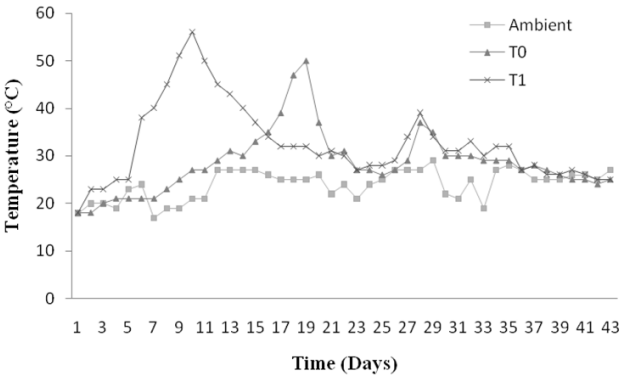

Figure 1. Variations of temperature in compost pots during the composting period.

pulp have been successfully employed for mass production and optimum growth of fungi during the fermentation process (Vijayendra et al., 2001; Singh et al., 2012). At this phase, the breakdown of organic substances takes place because of microbial activity which might be responsible for the increased temperature (Meng et al., 2019). A comparable finding was stated during the green waste composting with a 4% maifanite additive (Yin et al., 2021). The cooling phase started after 16 days in the T1 whereas in T0 it was observed in 21 days. The temperature plummeted from 34 ºC to 27 ºC and again slightly increased for a very short period, but then lowered and stabilized at 25 ºC later on. For T0, the same pattern was also noted. As the temperature dropped during this stage, the rate of metabolic activity also decreased, signaling the beginning of the maturation phase (Bernal et al., 2009). At the beginning of the composting process, a highly fungal colony in the raw material of the T1 was observed with a slightly unpleasant odor for a few days, but, later on, the final product lacked odor.

pH is another crucial factor in the composting process as it supports microbial growth (Ge et al., 2022). The initial pH of the compost was 5.7 in both T0 and T1. In the case of T1, it drastically decreased in the initial 7 days, then gradually increased and reached 7.6 on the 21st day, and finally stabilized at 7.1 (Fig. 2). An analogous trend was noted in the case of T0 but occurred lately as compared to the T1, and stabilized at slightly acidic pH (6.6). The decline in pH in the early stage could be because of the rapid decomposition of organic matter, resulting in the generation of organic acids throughout the composting process. Afterward, the pH was increased which is possibly linked to the disintegration of organic acids and the generation of ammonia (Wu et al., 2022). The final compost in the T1 was slightly alkaline (pH 7.1) which suggests the suitability of the product for the growth and yield of seedlings (Bustamante et al., 2008).

Particle-size distribution and coarseness index (CI) of the compost product

The distribution of particle size is important for determining the compost's maturity since it indicates how much the complicated materials have broken down (Zhang and Sun, 2018). A compost is considered mature when its percentage of particles lies between 0.25 and 2.00 mm (Gabhane et al., 2012). In this ideal range, T1 had a higher ($p < 0.05$) percentage of particles than T0 with values of 74.00% and 62.62% respectively (Table 1). The current result is more or less in line with the range of 41.10 – 69.11% that has been recorded for green waste composting (Yin et al., 2021).

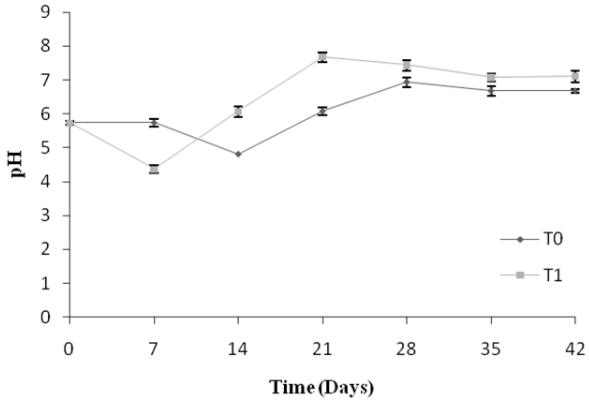

Figure 2. Changes in pH during the composting period in 7-day intervals.

Likewise, the value of CI was also higher ($p < 0.05$) in T1 (43.33%) than the T0 (28.84%) (Table 1). According to Jayasinghe (2012), high-quality compost has CI values between 30% to 45%; the treatment T1 had a CI value within this ideal range. Hence, the particle-size distribution and CI suggested the higher quality compost of the treatment T1 over T0.

Changes in total organic carbon (TOC)

It is often demonstrated that composting of any substrate results in decrease in TOC as it progresses (Mili and Tayung, 2024). The TOC content was observed to be low in both T0 and T1 regardless of raw SMS used in the experiment after 42 days of composting period. TOC content gradually decreased from 37.43% in the raw SMS to 25.15% and 17.48% in the T0 and T1 respectively (Table 2). A previous study has already documented the decrease in TOC in the final products of SMS composting (Meng et al., 2019). This trend is assignable to the microbial deterioration and mineralization of the compost materials (Srivastava et al., 2020), the consumption of organic carbon by microbes, and CO_2 released as a consequence of the respiratory activities of microbes (Karwal and Kaushik, 2020). A substantial drop in TOC in T1 compared to T0 suggested increased organic matter stabilization as a result of the mutual action of inoculated fungi and other microbes as well. The decline in TOC indicated the maturity of the end products.

Changes in C:N ratio

Composting efficiency depends critically on the C:N ratio of the substrate since it influences the pile's fermentation process. As shown in Fig. 3, the values of C:N declined significantly in T0 and T1, and the order of decreasing

Table 1. Particle-size distribution and Coarseness index (CI) of the final compost products.

Treatment	Particle size distribution (mm)							CI (> 1.00)
	> 5.00	5.00 – 2.00	2.00 – 1.00	1.00 – 0.50	0.50 – 0.25	< 0.25	0.25 – 2.00	
T0	3.58	11.34	13.92	23.47	25.23	22.46	62.62 ± 0.44^{b}	28.84 ± 0.60^{c}
T1	2.37	16.43	24.53	21.67	27.80	7.20	74.00 ± 0.81^{a}	43.33 ± 0.70^{d}

The values in each row (excluding values for 0.25–2.00 and CI) indicate the percentage in each size range. Values are mean ± standard deviation (SD); n = 3. Different letters in the same column indicate the significant difference at $p \leq 0.05$ (t-test, two-tailed).

Table 2. Macronutrient composition of the raw material and compost products (T0 and T1).

Substrate/Compost	TOC (%)	Total N (%)	Total K (%)	Total P (%)	Total Ca (%)	Total Mg (%)
Raw SMS	37.43 ± 0.31^{a}	0.83 ± 0.01^{c}	0.20 ± 0.07^{c}	0.49 ± 0.01^{c}	0.41 ± 0.02^{c}	0.23 ± 0.04^{c}
T0	25.15 ± 0.17^{b}	1.12 ± 0.11^{b}	0.21 ± 0.03^{b}	0.54 ± 0.03^{b}	0.65 ± 0.05^{b}	0.35 ± 0.04^{b}
T1	17.48 ± 0.05^{c}	2.52 ± 0.06^{a}	0.34 ± 0.03^{a}	0.98 ± 0.10^{a}	0.75 ± 0.05^{a}	1.33 ± 0.21^{a}

Mean value ±SD, n = 3; Different letters in the same column indicate statistically different values (Pair t-test $P < 0.05$, two-tailed).

value was T1 > T0. The initial C:N value of the raw SMS decreased from 44.8 to 22.52 in T0 and 6.93 in T1 in the final compost. This decreasing trend might be linked to the activity of microbes throughout the composting period that accelerate the release of CO_2 which leads to the decrease of TOC and enhanced nitrogen concentrations by mineralizing the substrate and breaking down organic materials (Ahmed and Deka, 2022). The C:N values with < 20 indicate the high quality of the compost, and values with < 15 confirm their excellence for agricultural application (Pandit et al., 2020). Our result also lies within this range in the case of T1 and the latter can be considered high-quality compost.

Macronutrients composition (TN, TP, TK, TCa, TMg)

The variation in TN, TP, TK, TCa, and TMg profiles in the raw SMS, T0, and T1 compost are presented in Table 2. The TN contents were increased by 1.35 and 3.03 folds in T0 and T1 respectively over the initial value of the raw SMS substrate. The increase in nitrogen content (TN) of the composting end-products may be attributed to several factors as reported previously by several researchers (Sun et al., 2021; Zawadzińska et al., 2021). For instance, the rate of NH_3 emission is the main reason responsible for the TN content of the composting end-products (Liu et al., 2020). The unpleasant odor was felt for a few days during the composting process in this study which indicated less emission of NH_3. Additionally, the production of fulvic and humic acids during the humification process, the loss of organic carbon from substrate consumption brought on by the active action of microbes, and the evaporation of water may all contribute to the increase in TN content levels in the final products (Samal et al., 2019).

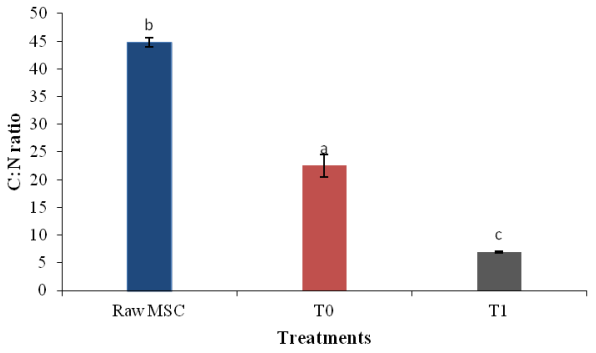

Figure 3. C:N ratios of the raw SMS, T0, and T1. Values are mean, n = 3, error bar indicates SD. Significant differences are indicated by different letters.

In addition to nitrogen, phosphorus is another essential nutrient in the compost product that is needed to grow plants. The increase in TP in both T0 and T1 was 1.10 and 2.00 folds respectively over the initial value of the raw SMS substrate. Similar results have been reported by Xu and Li (2017) in the composting of pig manure inoculated with microbial consortia consisting of two types of bacteria (*Bacillus subtilis*, *B. licheniformis*) and three types of fungi (*Phanerochaete chrysosporium*, *Trichoderma koningii*, *Saccharomyces cerevisiae*). It has been reported that the phosphatases released by the microbes are responsible for the generation of phosphorus from the substrate in the accessible forms by mineralization of organic matter (Pandit et al., 2020). Furthermore, the inoculation of fungi could be the fact that led to combined action with other microbes which resulted in a higher level of TP in T1 than T0 in the present study.

The TK increased up to 1.7 fold in T1 when compared to the value of raw SMS, whereas the value remained unchanged in T0. The increase of TK in the present study corroborates with the findings of Wang et al. (2021) where Chinese medicinal herbal residues were composted employing microbial agents (*Paenibacillus mucilaginosus*, *Cronobacter sakazakii*, *Klebsiella variicola*, *Kosakonia radicincitans*). Among the macronutrients, potassium is also essential for enzyme activation, photosynthesis, and protein synthesis. Plants can absorb potassium only in water-soluble forms, however, non-exchangeable potassium is also absorbed by plants if the exchangeable potassium level becomes low (Sánchez et al., 2017). From this perspective, the augment of TK in the compost products suggested the compost was conducive to potassium transformation that would be effective and advantageous for plant growth.

The increase in TCa was experienced in both T0 and T1 by 1.58 and 1.83 folds respectively over the initial value of the raw substrate used. Similarly, TMg was also enhanced by 1.52 in T0 and 5.78 in T1 end products. This result corroborates the description of Zhang and Sun (2014) where the SMS was co-composted with green waste. The formation of calcium carbonate by microorganisms' catalytic activity of carbonic anhydrous may be the cause of the rising TCa levels in the compost samples (Bose and Satyanarayana, 2017). Additionally, a rise in TCa concentrations in the compost samples may result from the release of Ca by the dissolution of Ca which is biologically bound by the reaction of organic acids that are produced at the late phase of composting (Gusain and Suthar, 2020). Similarly, it is also stated that the later stage of the composting process improves the TMg in

Table 3. Trace elements composition and microbial population of the raw material and compost products (T0 and T1).

Substrate/Compost	Trace elements		Microbial population	
	Fe (ppm)	Mn (ppm)	Bacteria (CFU/mL)	Fungi (CFU/mL)
Raw SMS	335 ± 4.509^{a}	11.31 ± 0.17^{a}	-	-
T0	75 ± 2.00^{c}	5.71 ± 0.03^{b}	$4.12 \times 10^{-7} \pm 0.22$	$3.46 \times 10^{-6} \pm 2.64$
T1	156 ± 3.05^{b}	0.00 ± 0.00^{c}	$6.52 \times 10^{-7} \pm 1.52$	$4.23 \times 10^{-6} \pm 0.57$

Mean value ±SD, n = 3; Different letters in the same column indicate statistically different values (Pair t-test $P < 0.05$, two-tailed). "-" denotes not being determined.

the compost samples by liberating naturally bound Mg into its free form (Malińska et al., 2016).

Trace elements composition (Fe, Mn)

The status of trace elements in the final product is presented in Table 3. The results reflected a decline in the concentration of Fe and Mn in both T0 and T1. The Fe concentration was found to be 4.47 fold decreased in T0 and 2.14 fold in T1 over the initial value of the raw substrate. Similarly, Mn concentration was lower by 1.98 fold over the raw material while the concentration of Mn could not be detected due to its low availability in the case of T1. Iron (Fe) and Mn play an essential role in microbial physiology as essential components of metabolic enzymes and regulatory proteins (Feng et al., 2021; Zhang et al., 2021). Therefore, the decrease in Fe and Mn may be ascribed to the high uptake by colonized microbes to perform their metabolic activities during the composting process. Moreover, the higher concentration of Fe recorded in T1 than in T0 might be allied to the physiological and metabolic roles of fungal consortia including other microbes contributing to the nutrient recovery process preventing the leaching of nutrients due to sprinkling of water during the composting process. However, previous studies have justified both increases and decreases in trace element concentrations. For instance, Larney et al. (2008) observed an increasing trend of trace elements including Fe and Mn during the composting of manure. In contradiction, Gurmessa et al. (2021) reported on the declining trend of trace elements during the composting or co-composting of agro-waste with biogas feedstock (maize silage, food processing waste, or poultry litter) which is consistent with the findings of our current investigation.

Microbial numbers analysis

The number of microbes (bacteria and fungi) was higher ($p < 0.05$) in T1 than in T0 (Table 3). The present outcome agrees with the report of Yin et al. (2021). The highest microbial abundance in T1 might be endorsed with the addition of FAS along with the fungal inoculum in the compost pile. The FAS was prepared with a mixture of ripened banana fruit and jaggery solution which are rich in some important nutrients like Fe, Ca, and K that could support the microbial growth in the T1 pile. Moreover, the soluble carbohydrates present in the compost substrate could also support microbial reproduction and activity (Larney et al., 2008). As a whole, the increase in the microbial number indicates enhanced stabilization of macro and micronutrients in the end product which is important for plant growth and development.

FTIR analysis

The existence or lack of functional groups confirmed through FTIR analysis suggests the degradation of an organic substrate during the bioconversion process (Deka et al., 2011). Table 4 lists the principal bands of the FTIR spectra that have been selected. The FTIR spectra bands were interpreted by referring to the articles of Deka et al. (2011); Salprima et al. (2013); and Zhuang et al. (2020). The common bands in all the samples were found at $3290 - 3346$ cm^{-1} (H-bonded OH groups of alcohols, phenols, and aldehydes), $2916 - 2917$ cm^{-1} (aliphatic C–H stretching), and $2846 - 2849$ cm^{-1} (C–H stretching for alkane) (see sup-

Table 4. The main absorbance bands in FTIR spectra of the samples and their assignments.

Band and peaks (cm^{-1})	Assignments	Remarks
1603	C-O/aromatic C-C stretching	Present only in raw SMS
1632-1633	C=C stretching for alkene	Present in both T0 and T1
1456	Stretching –C=O inorganic carbonate	Present only in T1
1368	C-O stretching/O-H deformation	Present only in T1
1372-1389	C–N stretching for amine groups	Present only in both raw SMS and T0
1034	C-O stretching, aromatic C-H in plane deformation	Present only in raw SMS
1050-1061	C-OH stretching vibration, C-O deformation	Present in both T0 and T1
782-791	N–H out of plane bending for amine and amide groups	Present in both T0 and T1

plementary data Fig. S1). A distinct peak at 1603 cm^{-1} (C-O/aromatic C-C stretching) was observed in raw SMS and absent in both T0 and T1 which indicates the breakdown of aromatic compounds during the composting process. Deformation of bands at or around 1050 cm^{-1}, 1061 cm^{-1}, and 1368 cm^{-1} was observed in both T0 and T1 which indicates the degradation of cellulose, hemicelluloses, fats, and lipid of the raw SMS (Ravindran and Sekaran, 2010). Moreover, peak intensities decrease by around 3500 cm^{-1} might be attributed to a decrease in atomic groups and OH, CH_2 which indicates the degradation of carbohydrates (Wang et al., 2004). Further, the peak at 1456 cm^{-1} (Stretching –C=O inorganic carbonate) provides a clue for the breakdown of carbonic acids during the composting process. Even though many FTIR bands are shared by both raw SMS and composting samples, the other IR spectra variations give pieces of evidence for the alternation of chemical components and transformations of SMS biomass during the composting period.

Correlation matrix analysis

As shown in Table 5, the correlation matrix revealed a significant relationship among the physicochemical compost parameters. The Spearman coefficient (r) ranges between -1 and $+1$, where zero denotes no correlation, 1 denotes perfect or complete correlation, and -1 indicates an inverse correlation between the variables (Akoglu, 2018). In this investigation, the perfect positive linear relationships among TN, TP, TK, Mg, Ca, Fe, and CI ($r = 1$, $p = 0.01$) were obtained whereas TOC, Mn, and C:N were negatively or inversely related ($r = -1$, $p = 0.01$) to the above parameters. The outcome of the present study indicated that if TOC decreases, the other parameters such as TN, TP, and TK gradually increase during the composting period. This might be due to the breakdown of organic substances and generation of nitrogenous compounds, mineralization of P, and K that are converted into available forms respectively by the action of microbes throughout the composting process (Meng et al., 2019). Moreover, when TOC tended to decrease, Mn concentration also decreased which suggests the perfect positive correlation ($p = 0.01$) between TOC and Mn. This may be endorsed with the utilization of Mn by microorganisms as it is an essential component of enzymes that are used in the deterioration of organic materials. Therefore, the correlation matrix analysis of physicochemical parameters could be used to determine compost maturity.

Phytotoxicity test

The germination index (GI) is an essential parameter to check the maturity and toxicity of composting end products (Boruah and Deka, 2021). An experiment on GI conducted on *P. vulgaris* seeds showed that the GI values were 97 and 151.15 for the seeds tested in T0 and T1 respectively (Fig. 4). It has been suggested that GI value of > 80 refers to a lack of phytotoxicity while a value of > 100 indicates the complete maturity of compost that can be applied as a biofertilizer (Wang et al., 2020). The highest GI in T1 might

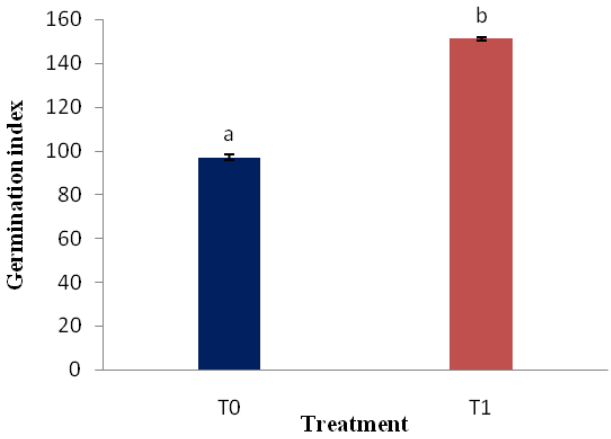

Figure 4. Germination index of *P. vulgaris* seeds in the final composts under different treatments.
n = 3, bars indicate SD. Different letters above the bars indicate the significant differences in the values among different treatments.

Table 5. Spearman's correlation among physico-chemical parameters during the composting process.

	TOC (%)	TN (%)	TP (%)	TK (%)	Mg (%)	Ca (%)	Mn (ppm)	Fe (ppm)	CI	C:N
TOC (%)	1									
TN (%)	-1**	1								
TP (%)	-1**	1**	1							
TK (%)	-1**	1**	1**	1						
Mg (%)	-1**	1**	1**	1**	1					
Ca (%)	-1**	1**	1**	1**	1**	1				
Mn (ppm)	1**	-1**	-1**	-1**	-1**	-1**	1			
Fe (ppm)	-1**	1**	1**	1**	1**	1**	-1**	1		
CI	-1**	1**	1**	1**	1**	1**	-1**	1**	1	
C:N	1**	-1**	-1**	-1**	-1**	-1**	1**	-1**	-1**	1

** correlation is significant at the 0.01 level (2-tailed).

be due to the biological activities of inoculated fungi which converted SMS into a fully decomposed and mature product (Boruah and Deka, 2021). Hence, the end product of T1 indicates a better rate of maturity and lack of phytotoxicity as compared to T0 compost.

4. Conclusion

Employing fungal consortia in composting can be a gainful and sustainable approach for the stabilization and bioconversion of different agro-wastes. This study explored the employment of lignocellulosic fungi in the composting of SMS obtained from the cultivation of Oyster mushrooms using citronella bagasse. The composting process was enhanced by the application of a fungal consortium along with FAS that improves the maturity and quality of the compost end-products. The decreased C:N ratio and the increase in the CI index, macronutrients, germination index, and early rise of temperature indicated the active participation of the fungal consortium in the degradation of SMS during the composting period. This study also provides a clue for the potentiality of this fungal consortium in the conversion of lignocellulosic wastes into value-added products that might be cost-effective and eco-friendly in the future. However, further study is required on gaseous emissions and their capture in future studies since methane and carbon emissions are one of the significant drawbacks of composting.

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Authors contributions
Study conception and design: Chiranjib Mili, Kumanand Tayung; data collection: Chiranjib Mili; analysis and interpretation of results: Chiranjib Mili, Pinky Rani Biswas, Subham Saha; draft manuscript preparation: Chiranjib Mili, Kumanand Tayung. The results were evaluated by all authors, and the final version of the manuscript was approved.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

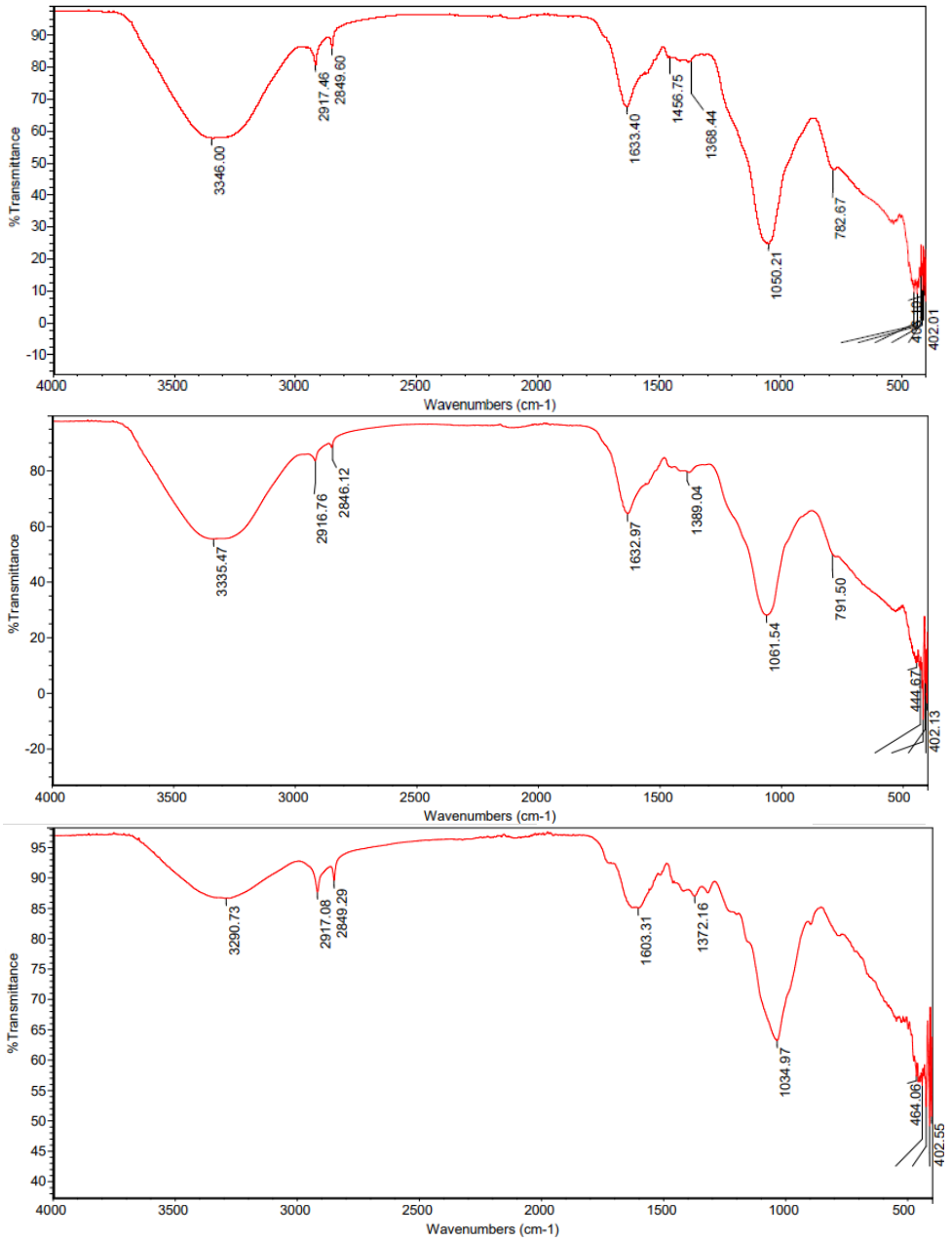

Figure S1. FTIR spectra of the raw SMS, T0, and T1 and its major band and peaks.