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Rapid composting of groundnut residues through novel microbial consortium: Evaluating maturity, stability, and microbial activity

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ABSTRACT

A laboratory pot experiment (Experiment 1) was conducted to determine the optimal ratio of groundnut haulm and shell as composting substrates. The aim was to identify the most effective combination for rapid decomposition under *in vivo* conditions. The experiment was carried out in 2022, from May to July, using a completely randomized design (CRD) with 6 treatments that were replicated 4 times. The treatment combinations in the pot experiment were as follows: T_1: haulm + shell (1:1), T_2: haulm + shell (2:1), T_3: haulm + shell (3:1), T_4: $T_1 + C_n$, T_5: $T_2 + C_n$, and T_6: $T_3 + C_n$. Here, C_n refers to the cellulose-degrading efficient microbial consortium containing bacterial strains *Priestia megaterium* DBJ6, *Micrococcus yunnanensis* DMB9, and fungal strains *Aspergillus foetidus* DAJ2, *Trichoderma atrobrunnium* DTJ4, and *Phanerochaete chrysosporium* CBS129.27. Based on the results (results of chemical and biological properties) of the pot experiment, treatment T_6 was considered the best treatment (the C/N ratio was 14.36 ± 0.444 after three months of decomposition) for further study under *in vivo* conditions. The *in vivo* experiment (Experiment 2) was conducted at the Jaguli Instructional Farm of Bidhan Chandra Krishi Viswavidyalaya, West Bengal, India, during the months of August to October in both 2022 and 2023 with two treatments: the normal composting treatment (NC) and the rapid composting treatment (RC). The findings of Experiment 2 showed that organic substrates degraded more quickly (within 90 days) during rapid composting, as evidenced by a decrease in the C/N ratio to below 15 (14.32 and 13.97 on day 90 in 2022 and 2023, respectively). Whereas, normal composting required more than 90 days to achieve a C/N ratio below 20 (23.80 and 23.15 on day 90 in 2022 and 2023, respectively). The RC treatment also showed a higher microbial population and enzyme activity compared to the NC treatment. Therefore, according to the results of this experiment, it can be concluded that the inoculation of the microbial consortium was more beneficial for accelerating the composting process under the same composting circumstances and substrate ratio.

1. Introduction

Crop residues possess significant value as a source of essential plant nutrients, hence enhancing resource utilization efficiency and promoting sustainability in agroecosystems (Dutta *et al.*, 2022). The combination of intensive agricultural practices and the burning of crop residue in the field has caused significant depletion in important nutrient reserves, soil microorganisms, and reduced crop yields. Additionally, this has led to the release of greenhouse gases, exacerbating environmental issues in the current climate conditions (Saikia *et al.*, 2019; Sharma *et al.*, 2021). The incineration of agricultural crop leftovers also contributes to an elevation in the concentrations of particulate matter and other detrimental air pollutants, which can lead to health problems, a reduction in the variety of cultivated land, and a deterioration in soil fertility (Raza *et al.*, 2022; Kumar *et al.*, 2023). In order to mitigate these adverse effects, alternate methods, such as *in situ* composting with the aid of microbial interventions, might be utilized (Bhuvaneshwari *et al.*, 2019; Biswas *et al.*, 2021; Semwal *et al.*, 2023). The application of microorganisms to crop residues for improved nutrient recycling and the development of valuable biomaterials is an innovative and promising field of research in secondary agriculture and microbial biotechnology (Mitra *et al.*, 2024). Composting entails the work of various microbial communities to biologically break down solid organic materials into mature, humidified, and stable material in an aerobic environment (Roy

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et al., 2022; Waqas *et al.*, 2023). Aeration is essential to the overall composting process as it promotes the microbial breakdown of organic materials and controls offensive chemicals (Ma *et al.*, 2019b). Composting using conventional procedures results in losses of between 30 and 50 % nitrogen and approximately 55 % organic carbon (Ravindran *et al.*, 2007). To address these problems, a new composting technique has emerged that produces ready-to-use compost in as little as 14 to 21 days (Irigoyen *et al.*, 2011). The process of microbial-assisted rapid composting technology is a sustainable approach that involves the introduction of a variety of microbial cultures or a consortium of microbes as an agent into the plant substrates employed for composting to improve nutrient cycling, decompose organic matter, and promote the general functioning of soil ecosystems (Bhattacharjya *et al.*, 2021; Dash *et al.*, 2021; Agrawal *et al.*, 2023; Janeeshma *et al.*, 2023). The use of microbial consortium as decomposing agents containing *Aspergillus* sp. (Sukaryani *et al.*, 2021; Sharma *et al.*, 2024), *Trichoderma* sp. (Chen *et al.*, 2019; Sarangi *et al.*, 2021; Sagarika *et al.*, 2022), *Phanerochaete* sp. (Chen *et al.*, 2019; Sagarika *et al.*, 2022), *Bacillus* sp. (Chukwuma *et al.*, 2021; Sharma *et al.*, 2024), and *Micrococcus* sp. (Hussain *et al.*, 2017) on crop residues can expedite the decomposition process, enhance the abundance of advantageous microorganisms in the soil, and ultimately yield advantages for agricultural ecosystems (Detain *et al.*, 2022; Sagarika *et al.*, 2022; Kumar *et al.*, 2023; Panneerselvam *et al.*, 2024). Typically, individual microbial strains are not highly effective at decomposing cellulose, and activating genes to increase cellulase production is not an economically viable approach. Microbial consortia composed of multiple microbial strains often demonstrate enhanced cellulase activity compared to individual strains, leading to increasing interest in their study (Roy *et al.*, 2022; Zhang and Dong, 2022). In addition, cellulosic crop leftovers have gained attention and interest due to their adaptability, abundant availability, renewable nature, low cost (Kumar and Chandra, 2020), and ability to be converted into environmentally friendly second-generation energy sources (Hernandez-Beltran *et al.*, 2019). Due to its high degree of crystallinity and complex structure (Kaur *et al.*, 2021), cellulose acts as the rate-limiting stage in the composting process (Agrawal *et al.*, 2018). Groundnut crop residues include large biomass, so they can also be utilized as compost that can improve soil health, and sustain productivity in the long run. The major constituent of groundnut pod shell is cellulose (65 %) (Fraps, 1919). Though groundnut shell contains 1.6–1.8 % N, 0.3–0.5 % P_2O_5, and 2–7 % K_2O (Anonymous, 1997), its manurial value is low because of the slow rate of decomposition. The rate of decomposition can, however, be enhanced by employing cellulolytic microorganisms. The organic material undergoes three distinct phases: a mesophilic phase characterized by the proliferation of microbiota, a thermophilic phase with intense biodegradation, and a final phase involving cooling, stabilization, and maturation. During this last phase, mesophilic organisms grow, and the compost undergoes humification (Waqas *et al.*, 2023). Microbes possess diverse metabolic capabilities that are pertinent to the conversion of complex organic wastes into soluble basic compounds through enzymatic action (Jat *et al.*, 2021). It is thought that a variety of hydrolytic enzymes regulate how quickly different substrates break down. Cellulases, which depolymerise cellulose; amylase, which hydrolyzes starch; protease, which is associated with N-mineralization; and phosphatase and arylsulphatase, which remove phosphate and sulphate groups from organic molecules, are significant enzymes in the composting process (Mondini *et al.*, 2004). Enzymatic activities can provide valuable information on the rate of organic matter breakdown and, subsequently, the stability of the end product (Jurado *et al.*, 2014). Compost stability and maturity can also be assessed by a number of parameters, including temperature, moisture content, color, odor, extractable carbon, C/N ratio, pH, phytotoxicity tests, or the evolution of humified compounds. These parameters are closely associated with changes in microbial activity, biomass, and biodiversity throughout the composting process (Pietro and Paola, 2004; Barrena *et al.*, 2008). A more sustainable and fruitful low-input agricultural system can be fostered with the correct preparation and use of compost (Golabi *et al.*, 2021). Therefore, the aim of this research work was to standardize the protocol for rapid decomposition of groundnut residues, study the physico-chemical properties of the prepared compost, and investigate the microbial activities at different phases of composting under different temperature regimes in terms of microbial population dynamics and enzymatic profiling.

2. Materials and methods

2.1. Details of the microbial consortium

An efficient cellulose-degrading microbial consortium culture containing bacterial strains *Priestia megaterium* strain DBJ6 [GenBank Accession Number (NCBI): PP082584, Repository Accession Number (NAIMCC): NAIMCC-B-03911], *Micrococcus yunnanensis* strain DMB9 [GenBank Accession Number (NCBI): PP082585, Repository Accession Number (NAIMCC): NAIMCC-B-03910], and fungal strains *Aspergillus foetidus* strain DAJ2 [GenBank Accession Number (NCBI): PP086700, Repository Accession Number (NAIMCC): NAIMCC-F-04568], *Trichoderma atrobrunnium* strain DTJ4 [GenBank Accession Number (NCBI): PP086699, Repository Accession Number (NAIMCC): NAIMCC -F-04569], and *Phanerochaete chrysosporium* strain CBS129.27 (Collection Acc. No.: 4955) was prepared in our laboratory (Fig. 1). The comprehensive procedure for preparing the liquid microbial consortium was well documented in our previously published research article (Roy *et al.*, 2024). After preparation of the consortium, glycerol, an osmo-protectant, was added in a suitable proportion and mixed gently. The prepared microbial consortium was then stored in glass bottles (Fig. 2), and this consortium was used in this study for the bio-augmentation of groundnut residues.

Note: NCBI – National Center for Biotechnology Information, part of the United States National Library of Medicine (NLM), a branch of the National Institutes of Health (NIH); NAIMCC – National Agriculturally Important Microbial Culture Collection, an International Depository Authority (IDA), a unit of the ICAR–National Bureau of Agriculturally Important Microorganisms (ICAR–NBAIM), Maunath Bhanjan, Uttar Pradesh, India, under the aegis of the Indian Council of Agriculture Research (ICAR) and the Department of Agricultural Research and Education (DARE), Government of India, New Delhi.

2.2. Pre-treatment of cellulosic substrates

The recently harvested groundnut haulms were gathered from the agricultural research farm of Bidhan Chandra Krishi Viswavidyalaya (State Agricultural University), West Bengal, India. They were then cut into pieces measuring 1–1.5 cm using scissors. Subsequently, the chopped haulms were immersed in a solution of 1 % NaOH, with a ratio of 10 ml of solution per gram of substrate. This means that for every one part of substrate, there were ten parts of solution. The soaking process lasted for 24 h. Following the process of neutralization through washing with distilled water, the pieces were subsequently dried for a duration of 6 h at a temperature of 80 °C. Before inoculation, the treated substrates underwent autoclaving for 20 min at a temperature of 121 °C (Mrudula and Murugammal, 2011; Xu *et al.*, 2021).

2.3. Standardization of the rate of consortium for inoculation through solid state fermentation

The process of solid-state fermentation was conducted in a 250 ml Erlenmeyer flask, which was filled with 20 g of groundnut haulms (cellulosic substrates) and moistened with 30 ml of distilled water. Subsequently, the flask underwent sterilization for a duration of 15 min at a temperature of 121 °C, followed by cooling to the ambient temperature. The consortium was inoculated at a concentration of 10 % (v/w) to the groundnut haulms (Mrudula and Murugammal, 2011), and then static incubated at a temperature of 30 ± 2 °C for a period of 7 days.

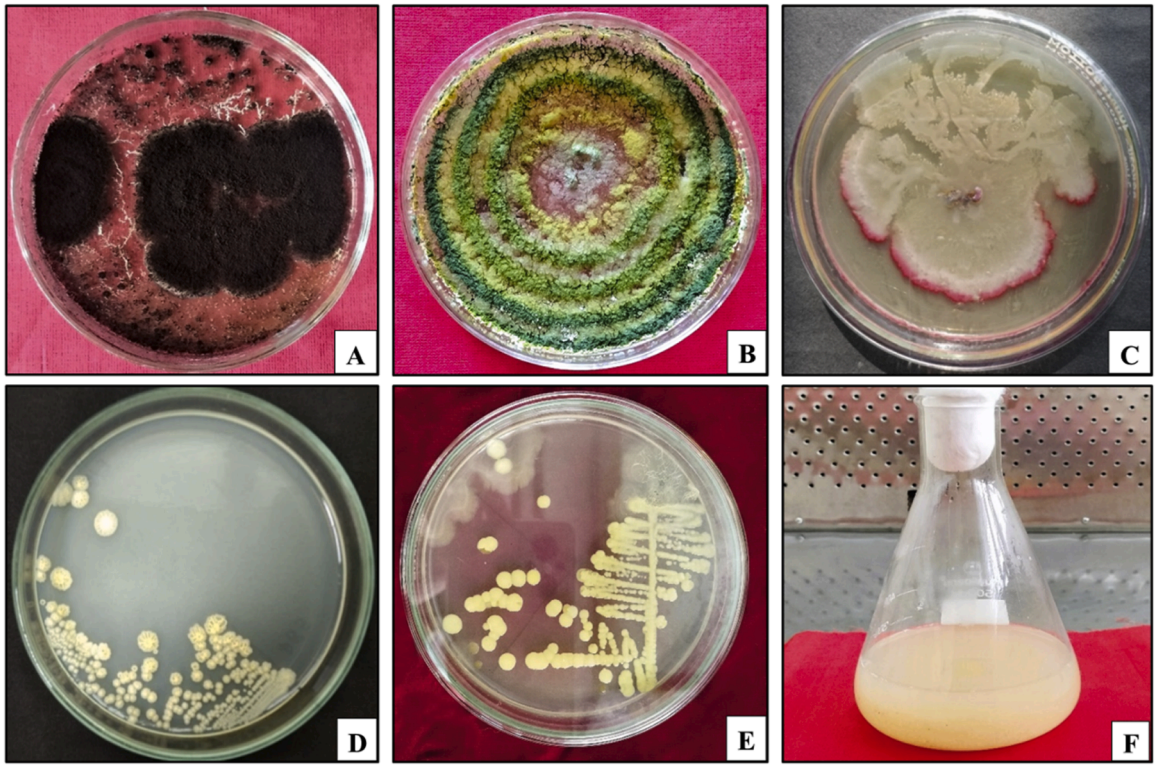

Fig. 1. Cellulolytic fungal and bacterial strains present in the consortium. **A:** *Aspergillus foetidus* strain DAJ2; **B:** *Trichoderma atrobrunnium* strain DTJ4; **C:** *Phanerochaete chrysosporium* strain CBS129.27; **D:** *Priestia megaterium* strain DBJ6; **E:** *Micrococcus yunnanensis* strain DMB9; **F:** Microbial consortium in CMC broth.

Fig. 2. Formulation of the cellulose decomposing liquid microbial consortium.

Thereafter, the incubation liquid was transferred to a 25 ml centrifuge tube, subjected to centrifugation at a speed of 12,000 rpm, and the resulting liquid above the sediment was utilized to measure the optical density (OD) value. The UV-Vis spectrophotometer ("Systronics microcontroller-based UV-Vis spectrophotometer model 117″, Systronics India Limited) was used to assess the variations in optical density (OD) values during distinct incubation/culture phases over a period of 0–7 days, specifically at a wavelength of 600 nm. The medium without any inoculum was considered blank control. Optical density (OD) measurements were taken in triplicate, and the resulting average values were recorded. The obtained data were subjected to statistical analysis to determine the standard deviation using SPSS software (version 20.0, SPSS Inc., Chicago, IL, USA). There is a strong correlation between the OD value and the concentration of microorganisms (Benner *et al.*, 2020;

Xu *et al.*, 2021).

Experiment 1. Composting of groundnut residues in the laboratory to standardize the protocol for rapid decomposition of residues (pot experiment)

2.4. Protocol to standardize the ratio of compost substrates

To determine the optimal ratio of groundnut haulm and shell for fast decomposition, 3 kg of groundnut residues, including dried groundnut haulms measuring 3–4 cm in size and groundnut pod shells in powdered form after decortication, were studied under pot experiment. The decomposition process was studied both with and without the addition of microbial culture. The aim was to find the most effective combination of groundnut haulm and shell that would result in rapid decomposition under *in vivo* conditions. The experiment was carried out in 2022, from May to July, using a completely randomized design (CRD) with 6 treatments that were replicated 4 times. The treatment combinations used in the pot experiment were as follows: T_1: haulm + shell (1:1), T_2: haulm + shell (2:1), T_3: haulm + shell (3:1), T_4: $T_1 + C_n$, T_5: $T_2 + C_n$, and T_6: $T_3 + C_n$. Here, C_n refers to the cellulose-degrading efficient microbial consortium. Throughout the experimental period, the laboratory maintained an average temperature of 32 ± 2 °C and a relative humidity of 80 %.

2.5. Method of composting

The microbial inoculant of the fungal and bacterial consortium was inoculated @ 10 % (v/w) of the groundnut residues in layers. For each treatment, 3 kg of groundnut residues were taken in different proportions in perforated plastic boxes wrapped with a 40-micron black-colored polythene sheet. The dimensions of each box were 0.4 m (L) x 0.3 m (W) x 0.3 m (H), with a volume of approximately 0.04 m^3. Thus, 3 kg of residues were evenly distributed throughout four layers. All the treatments were sprinkled with water as and when needed to maintain 40–60 % moisture content in the boxes (Hisham and Ramli, 2021). The boxes containing residues were considered for composting for a duration of 90 days. Samples were collected at a frequency of 30 days, starting from the beginning and continuing until 90 days, in order to analyze the chemical and biological properties. The contents of the boxes were rotated every 15 days to ensure proper air circulation and control the temperature (Nghi *et al.*, 2020).

2.6. Chemical analysis

The pH and electrical conductivity (EC) of the compost samples were measured using a digital pH meter equipped with a glass electrode ("Systronics microcontroller-based pH meter system with electrode and temperature probe model 361″, Systronics India Limited) and a digital electrical conductivity meter ("Systronics microcontroller-based conductivity meter system with cells and temperature probe model 306″, Systronics India Limited), respectively. The samples were mixed with distilled water at a ratio of 1:10 (w/v) before measurement. The estimation of the organic carbon content of the samples was conducted using the Walkley and Black rapid titration method (Walkley and Black, 1934), as outlined by Jackson (1973). The micro-Kjeldahl method ("Micro-Kjeldahl steam distillation assembly model MSGW-MKA", Malik Scientific Glass Works, India), the vanadate-molybdate phosphoric yellow color method using the UV-Vis spectrophotometer ("Systronics microcontroller-based UV-Vis spectrophotometer model 117″, Systronics India Limited), and the flame photometric method ("Systronics microcontroller-based flame photometer with compressor model 128″, Systronics India Limited) were used to determine the total nitrogen, total phosphorous, and total potassium content, respectively, according to the procedures described by Jackson (1973).

2.7. Analysis of biological properties

The compost samples were taken from the boxes after 90 days to determine the population of total bacteria, fungi, and actinomycetes. The samples were collected from boxes containing residue and air-dried. 10 g of air-dried samples were added to 90 ml of sterilized distilled water to make a 1:10 dilution (10^{-1} concentration), and to achieve a uniform suspension, the mixtures were vigorously shaken on a magnetic shaker for 20 to 30 min. Under laminar airflow ("Gi powder coated polished horizontal laminar airflow for laboratory", Sterile Tech India), it was serially diluted again by transferring 1 ml of suspension from the 10^{-1} marked conical flask to the first test tube containing 9 ml of sterilized distilled water to make a 1:100 dilution, and it was marked as 10^{-2} (Johnson and Curl, 1972). Similarly, it was further diluted up to a factor of 10^{-9}. Nutrient agar, Martins Rose Bengal agar, and Actinomycete isolation agar mediums were used for the enumeration of bacteria, fungi, and actinomycetes, respectively, following serial dilutions and the pour plate method (Zuberer, 1994). All of these media were autoclaved ("Vertical autoclave with both inner and outer chambers model UEW-501″, Universal Engineering Works, India) for 20 min at 121 °C to sterilize them. Following dilutions, 1 ml inoculum of serially diluted samples was poured into three different sterile media plates, and the petri plates were then placed in an incubator ("BOD incubator model EIE-202″, Eie Instruments Pvt. Ltd., India) at a temperature of 30 ± 2 °C for a period of 6–7 days for fungi and 1–2 days for bacteria and actinomycetes (Rathore *et al.*, 2014). After that, their population was counted and expressed per unit dry weight of substrate. Microbial colonies grown in every respective medium were counted using the following formula (Pepper *et al.*, 2004).

$$\textit{Viable cell count}\ \left(\textit{CFU}\ g^{-1}\ \textit{of dry compost}\right) = \frac{\textit{Number of colonies}}{\textit{Dilution factor}} \times \frac{1}{\textit{Dry weight of compost}}$$

2.8. Statistical analysis

The experiment was carried out using a completely randomised design (CRD), with each of the 6 treatments being replicated 4 times in order to minimize errors. The collected data were subjected to one-way analysis of variance (ANOVA) to determine any significant variations (at the $P \leq 0.05$ level) between the treatment data. Duncan's multiple range test (DMRT) was used to determine the mean ± standard error (SE) of the treatment data, following the method described by Duncan in 1955. The statistical analysis was performed using SPSS software (version 20.0, SPSS Inc., Chicago, IL, USA).

Experiment 2. Large scale production of compost in concrete vats under open conditions for final validation (*in vivo* experiment)

2.9. Method of preparation of compost in vats

Based on the results obtained from the laboratory pot experiment, the best treatment combination containing the optimum ratio of groundnut substrates along with consortium culture was taken into a vat [a concrete-made container; dimensions: 3 ft. (height) x 3 ft. (diameter); capacity: approximately 50 kg of groundnut residues] to prepare enriched compost on a large scale under open conditions for final validation. One un-inoculated control treatment was also maintained. So, the two treatments used in the *in vivo* experiment were the normal composting treatment (NC) and the rapid composting treatment (RC). The experiment was conducted at the Jaguli Instructional Farm of Bidhan Chandra Krishi Viswavidyalaya, West Bengal, India, during the months of August to October in both 2022 and 2023. Similar to the pot experiment, the composting was allowed for a period of 90 days. Water was sprayed on a frequent basis to keep the composting materials at a 40–60 % moisture level while they decomposed, and the ingredients

were well mixed. To ensure adequate aeration and temperature control, the composting piles were rotated every two weeks.

2.10. Recording of temperature in compost vats

The temperature was recorded at 6.00 a.m. in the morning at an interval of 7 days with the help of a compost thermometer at five random sites in three different layers (top layer: 10–20 cm, middle layer: 20–30 cm, and bottom layer: 30–40 cm) in both treated and untreated composting vats to monitor the progress of composting and was averaged (Sarma *et al.*, 2022). The ambient temperature was also simultaneously recorded.

2.11. Measurement of moisture content in compost vats

The gravimetric method, as described by the Bureau of Indian Standards (BIS, 1982), was employed to determine the weight reduction of compost samples after oven drying 5 g of sample to a temperature of 105 °C for a duration of 24 h (weighed repeatedly until a steady weight was obtained). This measurement was conducted at 7-day intervals to evaluate the moisture content.

2.12. Chemical analysis of compost prepared in concrete vats

In the final stage, chemical properties, *viz.*, pH, EC (ds m^{-1}), organic carbon (%), total nitrogen (%), total phosphorus (%), and total potassium (%) content, were determined following the standard methods (please refer to Section 2.6).

2.13. Microbial population dynamics at different phases of composting

The microbial population study was done at different phases of composting, *i.e.,* mesophilic, thermophilic, and maturation phases, following the standard procedures (please refer to Section 2.7).

2.14. Analysis of enzymatic activities for maturity and stability judgement of compost

Specific enzymatic activities were assessed in fresh, grounded, and sieved (<2 mm) compost samples at an interval of 30 days. Using sodium acetate-acetic acid buffer and 8 % soluble starch as the substrate, the amylase activity was measured at pH 5.2 using the Nelson-Somogyi method (Somogyi, 1952). Alkaline phosphatase activity was measured by incubating 0.5 g of compost sample with 1 ml of p-nitrophenyl phosphate (0.015 M) at 37 °C for 1 h. The p-nitrophenol produced was then quantified colorimetrically (Eivazi and Tabatabai, 1977). Using a Folin-Ciocalteau reagent, the protease activity was quantified colorimetrically by measuring the amount of amino acid released from 1 g of compost sample after it was incubated with 5 ml of sodium caseinate (2 %) for a period of 2 h at 50 °C. This technique uses the Folin reagent to determine the trichloroacetic acid-soluble tyrosine derivatives (Ladd and Butler, 1972). Cellulase activity was determined based on the colorimetric estimation of quantity of reducing sugars (glucose) released after the incubation of 5 g of compost sample with 15 ml of carboxymethyl cellulose sodium salt (0.7 %) at a temperature of 50 °C for a duration of 24 h, as described by Alef and Nannipieri (1995). In each case, the results were expressed as mg product g^{-1} h^{-1} on a dry weight basis.

2.15. Maturation studies of composting

Compost maturity was determined using pre-established compost stability and maturity characteristics (Ranalli *et al.*, 2001; Goyal *et al.*, 2005; Raj and Antil, 2011). After three months of decomposition, the compost from the rapid composting treatment was ready for use because it crumbled, turned dark brown, and had an earthy smell (Fig. 3). The synthesis of several microbial secondary metabolites may be responsible for the presence of earthy odors in the final compost (Li *et al.*, 2004; Sarma *et al.*, 2022). After composting, the end product did not reheat, and its temperature was below the outside air temperature. It was not moldy and rotten. Crumbly compost had a fluffy texture, but it did not need to be decomposed into powder form. Matured compost was passed through a 4 mm sieve. The material was kept for a considerable period once the composting appeared finished to confirm the stability of the decomposition.

3. Results and discussion

3.1. Standardization of the rate of consortium for inoculation based on variations in OD values during different incubation/culture phases (0–7 days)

As the groundnut haulms deteriorated, the OD value had a dramatic increase within the initial three days, rising from 0.24 to 0.86. Following the third day, the optical density (OD) value exhibited a gradual increase until it reached its maximum on the fifth day, with a value of 0.98. Subsequently, the optical density (OD) started to decline, reaching a value of 0.66 on the seventh day (Fig. 4). The OD value is directly correlated with the concentration of microorganisms (Benner *et al.*, 2020). The study found that there was a significant and rapid increase in the optical density (OD) value during the initial stage of incubation when the consortium was inoculated at a concentration of 10 % (v/w) to

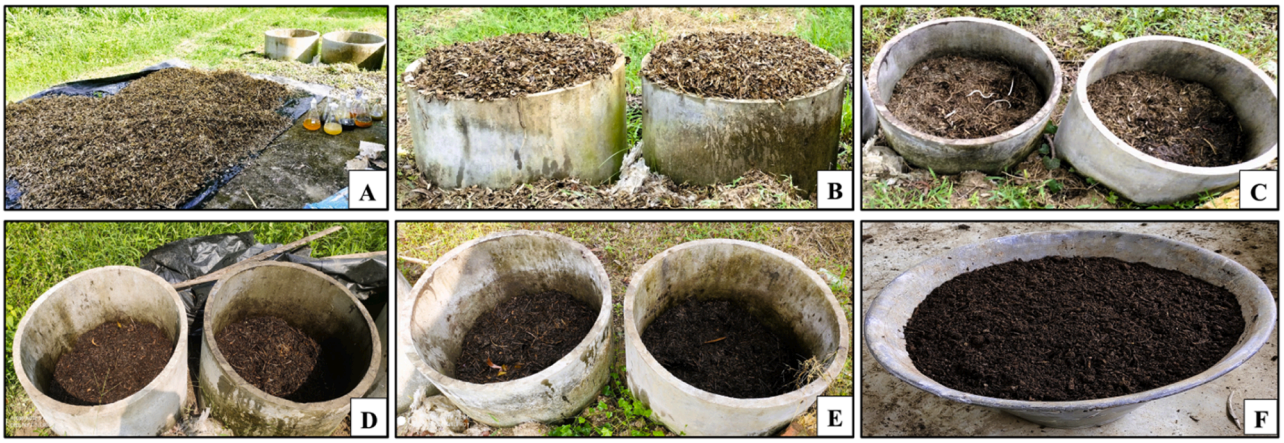

Fig. 3. Preparation of rapid compost in concrete vat. **A:** Mixing of groundnut haulm and shell in 3:1 proportion along with consortium culture; **B:** Initial stage of composting; **C:** After one month of decomposition; **D:** After two months of decomposition; **E:** After three months of decomposition; **F:** Matured compost.

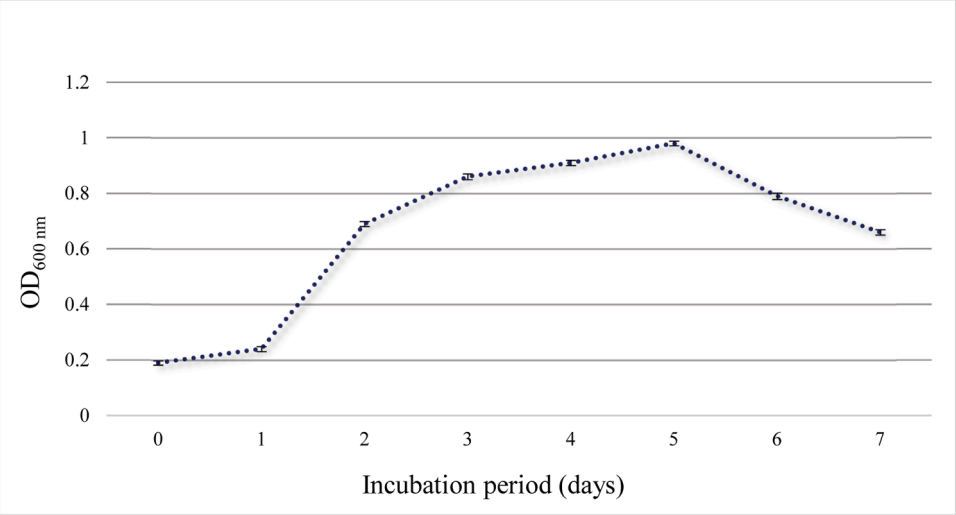

Fig. 4. Variations in OD values during different incubation/culture phases (0–7 days).

the groundnut haulms. This indicates that the concentration of microorganisms in the sample increased significantly during this period, which supports the degradation of groundnut haulms (Xu *et al.*, 2021).

3.2. Experiment 1: Studies of composting under pot experiment

3.2.1. Changes in chemical properties during the composting process

To explore the ratios of groundnut residue substrate with respect to their decomposition ability, different chemical properties like pH, EC (ds m^{-1}), C (%), N (%), C/N ratio, P (%), and K (%) were analyzed at the initial stage (Table 1) and at three months after decomposition (Tables 2 and 3). The treatments of different ratios of substrate, along with or without microbial culture, were assessed and compared. The determination of chemical parameters of the substrate used for composting at the initial stage revealed that there was no significant variation in pH, EC, organic carbon, total nitrogen, and C/N ratio, where total phosphorus and total potassium content differed significantly.

Table 1
Initial chemical properties of groundnut residues under different ratios.

Treatments	p^H	EC (dS m^{-1})	C (%)	N (%)	C: N	P (%)	K (%)
T_1: Haulm + Shell (1:1)	6.43 ± 0.163^a	4.12 ± 0.013^a	46.21 ± 0.278^a	1.09 ± 0.020^a	42.39 ± 0.715^a	0.86 ± 0.031^{bc}	0.93 ± 0.031^b
T_2: Haulm + Shell (2:1)	6.46 ± 0.085^a	4.09 ± 0.013^a	45.52 ± 0.223^a	1.16 ± 0.030^a	39.24 ± 1.167^a	0.92 ± 0.015^{bc}	0.97 ± 0.009^{ab}
T_3: Haulm + Shell (3:1)	6.41 ± 0.031^a	4.06 ± 0.027^a	44.66 ± 1.372^a	1.20 ± 0.037^a	37.22 ± 1.323^a	1.04 ± 0.032^a	0.99 ± 0.009^{ab}
T_4: $T_1 + C_n$	6.39 ± 0.048^a	4.08 ± 0.023^a	46.13 ± 0.330^a	1.12 ± 0.040^a	41.19 ± 1.811^a	0.84 ± 0.012^c	0.95 ± 0.008^b
T_5: $T_2 + C_n$	6.49 ± 0.039^a	4.10 ± 0.009^a	45.39 ± 0.275^a	1.15 ± 0.013^a	39.47 ± 0.307^a	0.93 ± 0.031^b	0.96 ± 0.018^b
T_6: $T_3 + C_n$	6.42 ± 0.025^a	4.07 ± 0.018^a	45.11 ± 0.363^a	1.18 ± 0.022^a	38.23 ± 0.908^a	1.02 ± 0.031^a	1.02 ± 0.023^a

The different *letters* following the data (mean ± SE) indicate significant (at the $P \leq 0.05$ level) differences based on Duncan's multiple range test (DMRT) (Duncan, 1955).

*C_n = Cellulose-degrading efficient microbial consortium [*Priestia megaterium* strain DBJ6 (PP082584, NAIMCC-B-03,911); *Micrococcus yunnanensis* strain DMB9 (PP082585, NAIMCC-B-03,910); *Aspergillus foetidus* strain DAJ2 (PP086700, NAIMCC-F-04,568); *Trichoderma atrobrunnium* strain DTJ4 (PP086699, NAIMCC-F-04,569); and *Phanerochaete chrysosporium* strain CBS129.27].

**GenBank Accession Numbers (NCBI): PP082584, PP082585, PP086700, PP086699.

**Repository Accession Numbers (NAIMCC): NAIMCC-B-03,911, NAIMCC-B-03,910, NAIMCC-F-04,568, NAIMCC-F-04,569.

Table 2
Chemical properties and NPK content after three months of decomposition of groundnut residues.

Treatments	p^H	EC (dS m^{-1})	C (%)	N (%)	P (%)	K (%)
T_1: Haulm + Shell (1:1)	7.69 ± 0.195^a	3.86 ± 0.160^a	34.82 ± 0.487^a	1.32 ± 0.042^c	0.95 ± 0.061^c	0.99 ± 0.096^b
T_2: Haulm + Shell (2:1)	7.52 ± 0.203^a	3.79 ± 0.281^a	33.52 ± 0.826^{ab}	1.36 ± 0.068^c	1.01 ± 0.027^c	1.06 ± 0.088^{ab}
T_3: Haulm + Shell (3:1)	7.34 ± 0.189^a	3.62 ± 0.138^a	32.12 ± 0.530^b	1.39 ± 0.080^{bc}	1.11 ± 0.016^b	1.12 ± 0.069^{ab}
T_4: $T_1 + C_n$	7.22 ± 0.207^a	3.51 ± 0.154^a	29.00 ± 0.412^c	1.44 ± 0.055^{bc}	1.16 ± 0.017^b	1.18 ± 0.043^{ab}
T_5: $T_2 + C_n$	7.16 ± 0.099^a	3.43 ± 0.098^a	27.16 ± 0.451^d	1.56 ± 0.040^{ab}	1.20 ± 0.013^b	1.22 ± 0.089^{ab}
T_6: $T_3 + C_n$	7.12 ± 0.324^a	3.36 ± 0.088^a	25.28 ± 0.323^e	1.76 ± 0.104^a	1.38 ± 0.016^a	1.29 ± 0.075^a

The different *letters* following the data (mean ± SE) indicate significant (at the $P \leq 0.05$ level) differences based on Duncan's multiple range test (DMRT) (Duncan, 1955).

*C_n = Cellulose-degrading efficient microbial consortium [*Priestia megaterium* strain DBJ6 (PP082584, NAIMCC-B-03,911); *Micrococcus yunnanensis* strain DMB9 (PP082585, NAIMCC-B-03,910); *Aspergillus foetidus* strain DAJ2 (PP086700, NAIMCC-F-04,568); *Trichoderma atrobrunnium* strain DTJ4 (PP086699, NAIMCC-F-04,569); and *Phanerochaete chrysosporium* strain CBS129.27].

**GenBank Accession Numbers (NCBI): PP082584, PP082585, PP086700, PP086699.

**Repository Accession Numbers (NAIMCC): NAIMCC-B-03,911, NAIMCC-B-03,910, NAIMCC-F-04,568, NAIMCC-F-04,569.

Table 3
Changes in the C/N ratio during different decomposition periods.

Treatments	C/N ratio		
	After 1 month	After 2 months	After 3 months
T_1: Haulm + Shell (1:1)	34.73 ± 0.992^{a}	28.97 ± 0.437^{a}	26.38 ± 0.401^{a}
T_2: Haulm + Shell (2:1)	32.20 ± 0.862^{b}	27.35 ± 1.748^{ab}	24.65 ± 0.590^{ab}
T_3: Haulm + Shell (3:1)	31.06 ± 0.526^{bc}	25.46 ± 0.827^{bc}	23.11 ± 1.196^{b}
T_4: T_1 + C_n	30.49 ± 0.911^{bcd}	23.25 ± 0.474^{cd}	20.14 ± 0.589^{c}
T_5: T_2 + C_n	29.19 ± 0.569^{cd}	21.99 ± 0.639^{de}	17.41 ± 0.735^{d}
T_6: T_3 + C_n	28.08 ± 0.756^{d}	19.72 ± 0.416^{d}	14.36 ± 0.444^{e}

The different *letters* following the data (mean ± SE) indicate significant (at the $P \leq 0.05$ level) differences based on Duncan's multiple range test (DMRT) (Duncan, 1955).
*C_n = Cellulose-degrading efficient microbial consortium [*Priestia megaterium* strain DBJ6 (PP082584, NAIMCC-B-03,911); *Micrococcus yunnanensis* strain DMB9 (PP082585, NAIMCC-B-03,910); *Aspergillus foetidus* strain DAJ2 (PP 086700, NAIMCC-F-04,568); *Trichoderma atrobrunnium* strain DTJ4 (PP 086699, NAIMCC-F-04,569); and *Phanerochaete chrysosporium* strain CBS129.27].
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3.2.1.1. pH profile during the composting process. pH is a crucial factor for evaluating the compost's quality during the decomposition phase and is considered an indicator of the breakdown and stabilization process. It is essential to do a pH test on compost before application because a pH value above 8.5 can lead to ammonia volatilization, the development of bad smells, and harm to plant roots. Maintaining a neutral pH level facilitates the optimal rate of breakdown and confirms the stabilization of compost. A pH close to neutral allows a wider range of microbes to flourish and decompose organic substances (Lunag and Boado, 2021). A perusal of the experimental results reveals that, irrespective of the treatments given, the pH increased consistently as the number of composting days increased, reaching its highest point on the last or final day (the 90th day) of the experiment. After three months of decomposition, the pH readings raised from the initial value of 6.43 recorded on the 0th day to 7.34 on the final day (average value of T_1, T_2, T_3, T_4, T_5, and T_6 at the 0th and 90th days, respectively) (Tables 1 and 2). The increase in pH values was caused by the release of ammonia resulting from the initiation of the proteolytic process (Batham *et al.*, 2014; Sarma *et al.*, 2022). The increase in pH during composting was likewise confirmed by Jang *et al.* (2002), who also claimed that the conversion of N_2 components in the compost into ammonia through ammonification was the cause of this increase. The pH of the compost stabilized between 7.12 ± 0.324 (T_6) and 7.69 ± 0.195 (T_1) on the 90th day of composting, indicating that the compost had reached a stable state (Table 2). This pH value comes within the anticipated range of 7.0–8.0, which is considered suitable for compost stabilization (Sarma *et al.*, 2022; Yang *et al.*, 2023). The outcomes obtained are consistent with the findings of previous studies conducted by Garg *et al.* (2006); Suthar (2009); and Patidar *et al.* (2013). The pH value further decreased under microbial inoculation of groundnut substrates over without inoculation, and the lowest value (7.12 ± 0.324) was obtained from treatment T_6 (haulm + shell @ 3:1 + C_n) on the 90th day (Table 2). The pH change was caused by the mineralization of nitrogen and phosphorus into nitrites/nitrates and orthophosphates (Ndegwa and Thompson, 2000; Yang *et al.*, 2023) and the decrease in pH under the microbially inoculated treatments was a result of the production of acids from the vigorous fermentation of carbohydrates during the rapid decomposition process by microbial metabolism (Benito *et al.*, 2003; Batham *et al.*, 2014; Sarma *et al.*, 2022).

3.2.1.2. Changes in electrical conductivity during the composting process. Electrical conductivity (EC) is a crucial element in the composting process, primarily present as ions within the compost extract. EC is a measure of the mineralization rate and soluble salt concentration in compost (Yang *et al.*, 2023). It indicates the level of salinity in the final compost product, which can have negative consequences on normal plant growth, such as low germination rate and wilting, due to phytotoxic or phytoinhibitory effects (Lin, 2008; Sharma *et al.*, 2014). Excessive levels of EC can be detrimental to crops when compost fertilizer is applied. Data depicted in Tables 1 and 2 shows that for all the treatments, the EC value decreased with increasing the composting period and stabilized between 3.36 ± 0.088 dS m^{-1} (T_6) and 3.86 ± 0.160 dS m^{-1} (T_1) on the final day or the 90th day of the experiment (Table 2). Typically, an EC value of less than 4 dS m^{-1} is considered optimal for fully matured compost used for agricultural applications (Al-Turki *et al.*, 2013). After three months of decomposition, all the EC values of this present experiment came within the desirable upper limit of matured compost, indicating its maturity and stability. The same findings were also reported by Sharma *et al.* (2014). Even though a decreasing trend of EC value was noticed for all the treatments at the 90th day of the experiment from its initial level, the EC value further decreased under microbial consortium-inoculated treatments than the un-inoculated ones, and T_6 treatment (haulm + shell @ 3:1 + C_n) had the lowest best EC value of 3.36 ± 0.088 dS m^{-1}. Ammonia volatilization and mineral salt precipitation are potential factors that may contribute to the decrease in electrical conductivity during the later stages of composting (Zhang *et al.*, 2017; Wei *et al.*, 2022).

3.2.1.3. Changes in organic carbon and total nitrogen content during composting. The crucial factors determining compost quality are its stability and maturity. Their relationship is determined by the extent to which the organic matter has been decomposed and stabilized over the course of composting (Ren *et al.*, 2019). Generally, carbon serves as the primary energy source for the growth of microorganisms. Data presented in Tables 1 and 2 shows that, as the decomposition period increased, organic carbon (OC) content gradually decreased from its initial value of 45.50 % to 30.32 % on the final day (average value of T_1, T_2, T_3, T_4, T_5, and T_6 at the 0th and 90th days, respectively), and irrespective of the treatments given, it was found to be minimum after three months of decomposition. The decline in overall organic carbon content during the process of composting was due to the consumption of carbon by microorganisms for their growth and metabolic processes, leading to the release of CO_2 as a byproduct of their metabolic activities. Similar findings were also reported by Benito *et al.*, 2003; Sharma *et al.*, 2014; Abdel-Rahman *et al.*, 2016; and Sarma *et al.*, 2022. Different ratios of substrate, along with or without the microbial consortium, had a significant impact on the decomposition of organic carbon at the final stage (on the 90th day) of composting. Regardless of the substrate ratios, the treatments that were infected with the microbial consortium (T_4–T_6) exhibited a substantial drop in carbon content (Zhou *et al.*, 2015; Li *et al.*, 2020) compared to the treatments that were not inoculated (T_1–T_3), and the lowest organic carbon content (25.28 ± 0.323 %) was recorded at treatment T_6 (haulm + shell @ 3:1 + C_n), which differed significantly from all other treatments (Table 2). In the case of treatments T_4, T_5, and T_6, there was a 37.13 %, 40.16 %, and 43.96 % reduction in organic carbon content after three months of decomposition from the initial level, respectively. A higher rate of organic carbon breakdown in T_6 suggests that the compost from this treatment was of higher quality or more stable at the end of the composting process (Sharma *et al.*, 2017; Lalremruati and Devi, 2021). The notable reduction in organic carbon content under the microbially inoculated treatments might be due to the rapid loss of carbon in the compost samples in the form of carbon dioxide emissions when inoculated with mixed cultures. This aligns with the findings of Makan and Mountadar (2012), Jusoh *et al.* (2013), Sharma *et al.* (2014); Abdel-Rahman *et al.* (2016) and Sarma *et al.* (2022).

Nitrogen (N) is a crucial component for the composting process as it directly influences the proliferation of microorganisms. Data on the

percentage of nitrogen during the composting process reveals that nitrogen content varied with the decomposition period and nature of the substrates used. It is believed that both the initial nitrogen content in the substrate and the degree of decomposition influence the final nitrogen content of compost (Kaviraj and Sharma, 2003). The lowest nitrogen content values were observed at the 0th day (Table 1) in all treatments (ranging from 1.09 ± 0.020 % to 1.20 ± 0.037 %; all were non-significant at $P \leq 0.05$), which increased significantly to the range of 1.32 ± 0.042 % to 1.76 ± 0.104 % on the final day after three months of decomposition (Table 2). The same finding was also reported by Abdel Rahman *et al.* (2016) and Sarma *et al.* (2022). Data depicted in Table 2 also reveals that the substrate ratio had a positive impact on the N content, and higher N content was recorded with the substrate ratio of 3:1 (haulm + shell) over other ratios of substrate (2:1 and 1:1). Irrespective of the substrate ratios, N content further increased when substrates of all ratios were inoculated with the microbial consortium, and significantly higher N content (1.76 ± 0.104 %) was found in treatment T_6 (haulm + shell @ 3:1 + C_n) on the 90th day, with a 49.15 % increase from the initial value. This was due to the concomitant oxidation of organic matter by microorganisms during the composting process, which resulted in an increase in nitrogen content in the compost (Wang *et al.*, 2017; Wei *et al.*, 2022). This is in accordance with the reports of Lee *et al.* (2002) and Sharma *et al.* (2014).

3.2.1.4. Changes in the C/N ratio during the composting process. Microorganisms primarily utilize carbon as a source of energy and retain a little quantity of nitrogen for their growth. Specifically, fungi, bacteria, and actinomycetes require both carbon and nitrogen for their growth and proliferation. Microbes degrade the carbon and nitrogen content of the substrates throughout the composting process, leading to a change in the ratio of carbon to nitrogen (Karadag *et al.*, 2013; Sarma *et al.*, 2022). The initial C/N ratio was estimated in the range of 37.22 ± 1.323 to 42.39 ± 0.715 at the 0th day (Table 1). For all the treatments, the C/N ratio started to decline after the first month of the decomposition period, and finally it reached its lowest value after three months of decomposition, ranging from 14.36 ± 0.444 to 26.38 ± 0.401 on the 90th day (Table 3). Changing the substrate ratios, with or without the microbial consortium, had a significant effect on how quickly the organic carbon and nitrogen in the substrate broke down during the composting period, hence positively impacting the C/N ratio as well. Regardless of the substrate ratios, the microbial consortium-inoculated treatments (T_4–T_6) significantly reduced the C/N ratio (Zhou *et al.*, 2015; Li *et al.*, 2020) compared to the un-inoculated treatments (T_1–T_3), with treatment T_6 (haulm + shell @ 3:1 + C_n) recording the lowest best C/N ratio of 28.08 ± 0.756, 19.72 ± 0.416, and 14.36 ± 0.444 after one, two, and three months of decomposition, respectively (Table 3). The significant decrease in the C/N ratio in treatment T_6 suggests that T_6 is highly efficient in facilitating the rapid decomposition of groundnut residues. A C/N ratio below 20 indicates a high level of organic matter stabilization and a good level of organic waste maturity (Suthar, 2008; Batham *et al.*, 2014), but a ratio below 15 is recommended for agronomic purposes (Soobhany *et al.*, 2017; López *et al.*, 2021). This result aligns with the findings of Makan and Mountadar (2012); Jusoh *et al.* (2013); Sharma *et al.* (2014); Abdel-Rahman *et al.* (2016); and Sarma *et al.* (2022), who reported that the decrease in the C/N ratio is mainly caused by the quick depletion of carbon in the compost samples. This depletion may be attributed to the introduction of efficient consortium cultures, which leads to an enhanced loss of carbon in the form of CO_2 emissions through microbial respiration, and the nitrogen content increases owing to a concentration effect, resulting in a decreased C/N ratio (Sharma *et al.*, 2014; Wei *et al.*, 2022).

3.2.1.5. Changes in the total phosphorous and potassium content during composting. Phosphorous (P) is an essential primary nutrient required for root growth and development of plants. Potassium (K) is also an essential element that significantly contributes to plant growth, especially in root elongation, protein synthesis, ion balance, and the photosynthesis process. The phosphorous and potassium content values were lowest on the 0th day (Table 1) in all treatments, ranging from 0.84 ± 0.012 to 1.04 ± 0.032 % and 0.93 ± 0.031 to 1.02 ± 0.023 % (all statistically significant at $P \leq 0.05$), respectively. These values increased significantly to the range of 0.95 ± 0.061 to 1.38 ± 0.016 % for phosphorous and 0.99 ± 0.096 to 1.29 ± 0.075 % for potassium on the final day after three months of decomposition (Table 2). Varying substrate ratios, with or without the microbial consortium, significantly affected the P and K content at both the beginning (on day 0) and the end of the composting process (on day 90). Irrespective of the substrate ratios, the P and K content showed additional increases when all substrate combinations were inoculated with the microbial consortium. Treatment T_6 (haulm + shell @ 3:1 + C_n) exhibited the highest P and K content, reaching 1.38 ± 0.016 % and 1.29 ± 0.075 % on the 90th day (Table 2), with an increase of 35.29 % and 26.47 % from their initial level (on day 0), respectively. The increase in phosphorus and potassium levels was attributed to the acid produced by microorganisms, which plays a significant role in solubilizing insoluble P and K (Hoekstra *et al.*, 2002; Batham *et al.*, 2014).

3.2.2. Changes in the microbial population under different treatments after three months of decomposition of groundnut residues

The pot experiment data on the microbial population after three months of decomposition of groundnut residues reveals that the population of total bacteria, fungi, and actinomycetes differed significantly (all were significant at $P \leq 0.05$) among the treatments based on different substrate ratios and microbial inoculation (Table 4). When comparing the microbial population among different substrate ratios under both un-inoculated and inoculated conditions, the data (Table 4) demonstrates that the substrate ratio of 3:1 (haulm + shell) resulted in a lower microbial count compared to other substrate ratios (2:1 and 1:1). The microbial population again decreased when substrates of all ratios were inoculated with the microbial consortium, and the significantly lowest count of total bacteria [(12.23 ± 0.111) × 10^9 CFU g^{-1}], fungi [(51.26 ± 0.409) × 10^5 CFU g^{-1}] and actinomycetes [(21.23 ± 0.142) × 10^7 CFU g^{-1}] was found in treatment T_6 (haulm + shell @ 3:1 + C_n) on the 90th day. The decline in the microbial population in T_6 might be due

Table 4
Changes in the microbial population after three months of decomposition of groundnut residues.

Treatments	Total Bacteria (1×10^9) CFU g^{-1}	Total Fungi (1×10^5) CFU g^{-1}	Total Actinomycetes (1×10^7) CFU g^{-1}
T_1: Haulm + Shell (1:1)	17.84 ± 0.151^a	78.42 ± 1.006^a	30.25 ± 0.106^a
T_2: Haulm + Shell (2:1)	16.75 ± 0.107^b	69.74 ± 1.151^b	28.03 ± 0.128^b
T_3: Haulm + Shell (3:1)	15.98 ± 0.097^c	63.59 ± 0.864^c	26.86 ± 0.198^c
T_4: T_1 + C_n	13.63 ± 0.127^d	56.97 ± 0.771^d	23.16 ± 0.162^d
T_5: T_2 + C_n	12.97 ± 0.118^e	54.84 ± 1.140^d	22.29 ± 0.114^e
T_6: T_3 + C_n	12.23 ± 0.111^f	51.26 ± 0.409^e	21.23 ± 0.142^f

The different *letters* following the data (mean ± SE) indicate significant (at the $P \leq 0.05$ level) differences based on Duncan's multiple range test (DMRT) (Duncan, 1955).

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to the depletion of organic carbon sources after the rapid breakdown of groundnut residues by microorganisms during the early phases of composting, which is crucial for their proliferation (Ogunyewo and Olajuyigbe, 2016). After three months of decomposition, the significant decrease in the microbial population in treatment T_6 indicates that T_6 is highly efficient at speeding up the breakdown of groundnut wastes, resulting in a stable and mature compost.

3.3. Experiment 2: Studies of composting under in vivo experiment

Based on the results (results of chemical and biological properties) of the pot experiment under laboratory conditions, treatment T_6 (haulm + shell @ 3:1 + C_n) was considered the best treatment for further study under *in vivo* conditions. An un-inoculated control treatment (haulm + shell @ 3:1) was also maintained. So, the two treatments used in the *in vivo* experiment were the normal composting treatment (NC) and the rapid composting treatment (RC).

3.3.1. Temperature profile during the composting process

Temperature is an important ecological aspect in the composting process because it promotes the decomposition of organic matter and helps to eradicate harmful microorganisms and pathogens that may negatively impact soil organisms (Lalremruati and Devi, 2021). Temperature fluctuations directly influence the activity of microorganisms and the stability of organic materials throughout the composting process (Barthod *et al.*, 2018; Zhang *et al.*, 2018). Table 5 summarises the impact of the microbial consortium on composting temperature. The mesophilic phase could not be distinguished in either the NC or RC treatments due to a rapid increase in temperature within the first week of both regimens from their initial temperature of 31.82 °C recorded at the beginning of composting (on the 0th day). As can be seen, the maximum temperatures of 61.79 °C (average of 2022: 60.56 °C and 2023: 62.02 °C) and 55.68 °C (average of 2022: 56.00 °C and 2023: 55.36 °C) were recorded on the 7th day, with a high temperature (>50 °C) period (thermophilic phase) of 28 days and 35 days in the case of RC and NC treatment, respectively.

Table 5
Changes in temperature during normal composting and rapid composting of groundnut residues.

Composting time (7 days interval)	Temperature (°C)					
	Normal composting (Haulm + Shell in 3:1)			Rapid composting (Haulm + Shell in 3:1) + C_n		
	2022	2023	Mean	2022	2023	Mean
0	32.24	31.40	31.82	32.24	31.40	31.82
7	56.00	55.36	55.68	60.56	62.02	61.79
14	54.05	53.95	54.00	60.38	59.84	60.11
21	51.86	52.69	52.28	57.48	56.67	57.08
28	51.69	51.86	51.78	55.12	53.50	54.31
35	50.11	50.72	50.42	49.34	47.26	48.30
42	49.38	48.82	49.10	45.67	44.05	44.86
49	46.59	47.30	46.95	39.19	38.25	38.72
56	44.73	45.32	45.03	35.62	36.09	35.86
63	40.25	42.00	41.13	31.41	30.95	31.18
70	37.79	38.25	38.02	28.15	27.39	27.77
77	36.52	37.34	36.93	24.88	24.12	24.50
84	36.26	36.03	36.15	22.53	21.75	22.14
90	34.61	33.94	34.28	22.26	21.34	21.80

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The composting temperature in this study fell within the range (±) of 32 to 62 °C as specified by the Ministry of Agriculture and Food (1996), indicating successful composting, and the temperature curves fluctuated in response to the rotation of the piles under both treatments. As a result of the accelerated breakdown in the inoculation treatment, the temperature dropped to lower levels compared to the control treatment towards maturity (Table 5). On the 90th day, the temperature of the RC treatment dropped to 22.26 °C and 21.34 °C (<22.42 °C and 22.75 °C of minimum air temperature) in 2022 and 2023, respectively. The gradual decrease of the internal temperature of compost below the ambient level (Table 6) by the 13th week in the RC treatment indicates that fermentation was almost complete and the compost mixture had fully decomposed and transformed into mature compost (Li *et al.*, 2020). At day 90, the temperature of the NC treatment was still higher than the maximum air temperature of 31.78 °C and 31.88 °C (Table 6), reaching 34.61 °C and 33.94 °C in 2022 and 2023, respectively. The higher internal temperature observed during the 13th week of NC treatment suggests that the NC material was still undergoing a somewhat slow process of decomposition. Slower decomposition can lead to a gradual production of heat, resulting in energy loss and a decrease in the accumulation of end products (Lalremruati and Devi, 2021). Therefore, according to the results of this experiment, it can be concluded that the inoculation of the microbial consortium was more beneficial for accelerating the composting process under the same composting circumstances and substrate ratio (Yang *et al.*, 2023).

3.3.2. Moisture content during the composting process

Water plays a crucial role in composting by facilitating the movement of nutrients and the breakdown of organic materials (Yang *et al.*, 2023). Keeping the water content at an adequate level during composting sustains microbial activities and enhances the degradation of organic matter. Microorganisms involved in composting use a significant amount of water, which subsequently evaporates over the entire process. When the moisture content drops, the rate of decomposition slows down (Bernal *et al.*, 2009). The inoculation treatment (RC) exhibited more moisture loss compared to the control treatment (NC) throughout the composting process (Table 7). As the compost matured, the moisture content of both treatments gradually decreased from 68.28 % at the start of composting (on day 0) to 40.06 % and 44.62 % at the end (on day 90) in the cases of RC and NC, respectively (mean value of 2022 and 2023). The variation in moisture content indicates that the microbial consortium in the inoculation pile was potentially more active than the indigenous microorganisms in the control pile (Li *et al.*, 2020).

3.3.3. Chemical properties of the finished compost

After three months of decomposition under open conditions, the chemical properties of NC and RC treatments showed a similar trend in both 2022 and 2023 (Table 8), as observed in the findings of the pot experiment (Table 2). Organic substrates degraded more quickly (within 90 days) during rapid composting, as evidenced by a decrease in the C/N ratio to below 15 (14.32 and 13.97 on day 90 in 2022 and 2023, respectively). Whereas, normal composting required more than 90 days to achieve a C/N ratio below 20 (23.80 and 23.15 on day 90 in 2022 and

Table 6
Ambient temperature during the composting period.

Year	Temperature (°C)					
	August		September		October	
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
2022	32.69	25.58	33.14	25.49	31.78	22.42
2023	32.53	25.88	32.91	25.84	31.88	22.75

Source: Department of Agricultural Meteorology and Physics, B.C.K.V., West Bengal, India.
Tmax and Tmin values are average of the whole month.

Table 7
Changes in moisture content during normal composting and rapid composting of groundnut residues.

Composting time (7 days interval)	Moisture content (%)					
	Normal composting (Haulm + Shell in 3:1)			Rapid composting (Haulm + Shell in 3:1) + C_n		
	2022	2023	Mean	2022	2023	Mean
0	68.00	68.56	68.28	68.00	68.56	68.28
7	65.42	66.67	66.05	65.15	66.01	65.58
14	64.15	64.39	64.27	62.06	63.58	62.82
21	63.24	64.05	63.65	58.85	60.77	59.81
28	61.52	63.14	62.33	55.40	56.63	56.02
35	58.73	60.08	59.41	53.00	54.32	53.66
42	57.04	58.33	57.69	51.52	52.25	51.89
49	54.59	56.11	55.35	48.39	50.01	49.20
56	52.00	53.85	52.93	45.89	47.21	46.55
63	49.19	51.17	50.18	44.14	45.19	44.67
70	48.54	49.06	48.80	42.07	42.23	42.15
77	46.65	47.99	47.32	41.64	42.00	41.82
84	45.88	46.00	45.94	40.69	40.31	40.50
90	44.51	44.73	44.62	40.26	39.86	40.06

*C_n = Cellulose-degrading efficient microbial consortium [*Priestia megaterium* strain DBJ6 (PP082584, NAIMCC-B-03,911); *Micrococcus yunnanensis* strain DMB9 (PP082585, NAIMCC-B-03,910); *Aspergillus foetidus* strain DAJ2 (PP 086700, NAIMCC-F-04,568); *Trichoderma atrobrunnium* strain DTJ4 (PP 086699, NAIMCC-F-04,569); and *Phanerochaete chrysosporium* strain CBS129.27].
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Table 8
Chemical properties and nutrient content of the finished compost prepared in concrete vats.

Parameters	Normal composting (Haulm + Shell in 3:1)			Rapid composting (Haulm + Shell in 3:1) + C_n		
	2022	2023	Mean	2022	2023	Mean
p^H	7.28	7.32	7.30	7.08	7.14	7.11
EC (dS m^{-1})	3.65	3.63	3.64	3.37	3.32	3.35
C (%)	33.56	32.41	32.59	25.21	24.87	25.04
N (%)	1.41	1.40	1.41	1.76	1.78	1.77
C: N	23.80	23.15	23.48	14.32	13.97	14.15
P (%)	1.07	1.12	1.10	1.36	1.43	1.40
K (%)	1.13	1.09	1.11	1.28	1.32	1.30

*C_n = Cellulose-degrading efficient microbial consortium [*Priestia megaterium* strain DBJ6 (PP082584, NAIMCC-B-03,911); *Micrococcus yunnanensis* strain DMB9 (PP082585, NAIMCC-B-03,910); *Aspergillus foetidus* strain DAJ2 (PP 086700, NAIMCC-F-04,568); *Trichoderma atrobrunnium* strain DTJ4 (PP 086699, NAIMCC-F-04,569); and *Phanerochaete chrysosporium* strain CBS129.27].
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2023, respectively). A significant decline in the C/N ratio, accompanied by an increase in total NPK values, indicated that the compost generated from the RC treatment was of high quality when it reached maturity.

3.3.4. *Influence of inoculation on microbial population dynamics at different phases of composting*

The study of microbial population dynamics at different phases of composting reveals that the highest populations of bacteria, fungi, and actinomycetes were observed during the mesophilic phase, followed by the thermophilic and maturation phases in both NC and RC treatments (Table 9). Specifically, the counts of bacteria and actinomycetes were higher than those of fungi in both the control and inoculation treatments throughout the whole composting process. In the same way, the number of mesophilic microbes was greater than that of thermophilic microorganisms, and mesophilic bacteria had the highest counts in both treatments. The drop in microbial population during the thermophilic stages of composting has been well documented (Ryckeboer *et al.*, 2003; Chroni *et al.*, 2009), and this phenomenon was also found in both treatments in this study; however, the degree to which microbial counts declined in the RC treatment during the maturation stages was significantly greater. Significant disparities emerge when comparing the microbial population between control and infected piles. Despite the similarities in trends, significantly higher counts of microorganisms were seen in the RC treatment during both the mesophilic and thermophilic phases (Table 9). During these initial phases of composting, the inoculated piles achieved and maintained higher thermal values for a longer period of time. Since microbial aerobic metabolism generates heat within the piles, these results may have been caused by a higher microbial population in infected piles (Insam and de Bertoldi, 2007; Jurado *et al.*, 2015). Due to an increased microbial population, cellulose began to degrade rapidly in the RC treatment, making the polymers more soluble and changing their structural makeup, favouring the enzymatic activity and development of microorganisms in a consistent manner. But during the maturation phase, RC treatment showed a lower microbial population than that of NC treatment. The decrease in the microbial population might be due to the depletion of organic carbon sources after the rapid breakdown of groundnut residues by microorganisms during the early phases of composting, which is essential for their growth. This drop can be linked to the decrease in the production of hydrolytic cellulase enzymes during the maturation stages of RC treatment, indicating a stable, mature compost (Ogunyewo and Olajuyigbe, 2016).

3.3.5. *Microbial enzymatic activities during the composting process*

3.3.5.1. Amylase activity. Amylases are enzymes that facilitate the breakdown of alpha-1, 4-glycosidic bonds in polysaccharides, resulting in the production of maltose, oligosaccharides, dextrin, and d-glucose by hydrolysis. The amylase activity in both the RC and NC treatments exhibited an initial rise up to 30 days, followed by a consistent decrease as the composting periods progressed (Table 10). At the 30th day of decomposition, the amylase content was higher in the RC treatment (10.98, 10.05, and 10.74 mg g^{-1} h^{-1} in 2022, 2023, and mean value of two years, respectively) as compared to the NC treatment (7.25, 7.60, and 7.43 mg g^{-1} h^{-1} in 2022, 2023, and mean value of two years, respectively). Irrespective of the treatments used, the results of this experiment showed that starch, the substrate material for glucose, degraded to its maximum level in 30 days, as evidenced by an increase in amylase activity during that time. Glucose serves as a readily available energy source for microorganisms and also enhances the process of compost biodegradation. The early breakdown of starch could be related to the proliferation of microorganisms during this initial stage (Bellia *et al.*, 2000). The amylase content decreased with increasing decomposition periods, and the minimum was recorded at 90 days of composting age in both NC (2.11 and 1.97 mg g^{-1} h^{-1} in 2022 and 2023, respectively) and RC (0.98 and 0.86 mg g^{-1} h^{-1} in 2022 and 2023, respectively) treatments. The presence of a significant amount of degradable organic substances in the original mixture likely promoted the growth of microorganisms and the synthesis of enzymes. As the available substrate reduced, the microbial population decreased, and the activity of the enzymes also dropped (Castaldi *et al.*, 2008). After a period of two and three months, the amylase activity was found to be greater in the NC treatment compared to the RC treatment (Table 10). This suggests that the NC material was still undergoing a relatively slow process of decomposition, while the RC treatment had almost completed the fermentation process and the compost mixture had fully decomposed, transforming into mature compost. These results align with the reports

Table 9
Microbial population dynamics at different phases of composting.

Treatment	Phases of composting	Total Bacteria (1×10^9) CFU g^{-1}			Total Fungi (1×10^5) CFU g^{-1}			Total Actinomycetes (1×10^7) CFU g^{-1}		
		2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
Normal composting	Mesophilic	20.25	21.97	21.11	78.26	80.08	79.17	32.64	32.43	32.54
(Haulm + Shell in 3:1)	Thermophilic	17.56	18.28	17.92	74.72	75.18	74.95	29.80	31.16	30.48
	Maturation	14.91	16.17	15.54	60.70	63.42	62.06	25.97	28.85	27.41
Rapid composting	Mesophilic	24.25	26.39	25.32	96.25	98.44	97.35	40.02	39.50	39.76
(Haulm + Shell in 3:1) + C_n	Thermophilic	20.96	23.22	22.09	83.86	87.60	85.73	33.91	35.29	34.60
	Maturation	13.84	11.52	12.68	50.57	52.39	51.48	20.62	21.35	20.99

*C_n = Cellulose-degrading efficient microbial consortium [*Priestia megaterium* strain DBJ6 (PP082584, NAIMCC-B-03,911); *Micrococcus yunnanensis* strain DMB9 (PP082585, NAIMCC-B-03,910); *Aspergillus foetidus* strain DAJ2 (PP086700, NAIMCC-F-04,568); *Trichoderma atrobrunnium* strain DTJ4 (PP086699, NAIMCC-F-04,569); and *Phanerochaete chrysosporium* strain CBS129.27].
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Table 10
Enzymatic activities for maturity and stability judgement of compost.

Treatment	Decomposition period	Amylase activity (mg g^{-1} h^{-1})			Alkaline phosphatase activity (mg g^{-1} h^{-1})		
		2022	2023	Mean	2022	2023	Mean
Normal composting	After 1 month	7.25	7.60	7.43	6.74	6.92	6.83
(Haulm + Shell in 3:1)	After 2 months	4.12	3.99	4.06	3.36	3.88	3.62
	After 3 months	2.11	1.97	2.04	1.69	1.75	1.72
Rapid composting	After 1 month	10.98	10.05	10.74	8.95	9.19	9.07
(Haulm + Shell in 3:1) + C_n	After 2 months	3.37	3.15	3.26	1.93	1.89	1.91
	After 3 months	0.98	0.86	0.92	0.94	1.00	0.97
Treatment	Decomposition period	Protease activity (mg g^{-1} h^{-1})			Cellulase activity (mg g^{-1} h^{-1})		
		2022	2023	Mean	2022	2023	Mean
Normal composting	After 1 month	3.12	3.04	3.08	0.47	0.51	0.49
(Haulm + Shell in 3:1)	After 2 months	3.41	3.56	3.49	0.62	0.70	0.66
	After 3 months	3.95	4.03	3.99	0.79	0.83	0.81
Rapid composting	After 1 month	4.78	4.16	4.47	1.48	1.56	1.52
(Haulm + Shell in 3:1) + C_n	After 2 months	3.10	2.88	2.99	0.54	0.62	0.58
	After 3 months	1.64	1.56	1.60	0.23	0.20	0.22

*C_n = Cellulose-degrading efficient microbial consortium [*Priestia megaterium* strain DBJ6 (PP082584, NAIMCC-B-03,911); *Micrococcus yunnanensis* strain DMB9 (PP082585, NAIMCC-B-03,910); *Aspergillus foetidus* strain DAJ2 (PP086700, NAIMCC-F-04,568); *Trichoderma atrobrunnium* strain DTJ4 (PP086699, NAIMCC-F-04,569); and *Phanerochaete chrysosporium* strain CBS129.27].
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of Raut *et al.* (2008).

3.3.5.2. Alkaline phosphatase activity. Phosphatase is an enzyme that has agricultural significance as it breaks down organic phosphorus molecules and converts them into various forms of inorganic phosphorus that can be readily absorbed by plants. The presence of phosphorylated substances serves as a substrate for microbes to synthesise phosphatase, resulting in phosphatase activity (Ayuso *et al.*, 1996). This activity is regarded as a generic microbial indicator (Spier and Ross, 1978). It serves as a crucial enzyme in the phosphorus cycle, which is triggered by the breakdown of carbohydrate-derived structures (such as cellulose) by enzymatic hydrolysis into cellobiose. Subsequently, cellobiose is further broken down into glucose by B-glucosidase. Phosphatase is an essential enzyme in the analysis of the composting process, as it is only produced by microbes and not derived from crop residues (Raut *et al.*, 2008). Table 10 explains the alkaline phosphatase activity in both NC and RC treatments. Alkaline phosphatase activity exhibited a similar pattern to that of amylase, with an initial increase up to the 30th day of the experiment, followed by a sharp decrease with the advancement of the composting periods, and the minimum activity was found after three months of decomposition (on day 90) in both treatments. The observed high initial activity could be linked to the substantial amount of organic phosphate compounds present in the composting mixture, which stimulated the growth of microorganisms and enzyme synthesis. As substrate availability decreased, the microbial population declined, leading to a decrease in enzyme activity (Castaldi *et al.*, 2008). On day 30, the RC treatment exhibited the highest activity levels (8.95 and 9.19 mg g^{-1} h^{-1} in 2022 and 2023, respectively) compared to the NC treatment (6.74 and 6.92 mg g^{-1} h^{-1} in 2022 and 2023, respectively). However, by days 60 and 90, the NC treatment demonstrated significantly higher alkaline phosphatase values compared to the RC treatment (Table 10), indicating that the NC treatment was decomposing at a slower rate, whereas the RC treatment had nearly finished the fermentation process, resulting in a matured compost (Raut *et al.*, 2008).

3.3.5.3. Protease activity. Protease plays a crucial role in initiating mineralization, a step that frequently determines the pace of the nitrogen cycle, and are essential enzymes in the composting process with significant functional roles (Ma *et al.*, 2019a). Protease activity plays a significant role in the nitrogen cycle by facilitating the breakdown of proteins into ammonia, specifically targeting short-chain polypeptide substrates through hydrolysis (Raut *et al.*, 2008). The results of the protease activity have been described in Table 10. Protease activity was clearly distinguished during the composting process. Like the other two enzymes (amylase and phosphatase), the protease activity showed an increasing trend up to the 30th day of the decomposition period (4.78

and 4.16 mg g^{-1} h^{-1} in 2022 and 2023, respectively), and subsequently started to decline as the composting period progressed, reaching its lowest point at the 90th day (1.64 and 1.56 mg g^{-1} h^{-1} in 2022 and 2023, respectively) of the RC treatment (Table 10). However, this decline was not as sharp as was observed in the activities of amylase and phosphatase. Protease activity and breakdown of proteins increased during rapid decomposition, indicating the efficacy of RC treatment, as ammonia was effectively removed through aeration (Ros *et al.*, 2006). The findings from this experiment indicate that protease activity trends differed between the NC and RC treatments. In the case of NC treatment, protease activity exhibited an upward trend towards maturity, reaching its peak on the 90th day of the decomposition period (3.95 and 4.03 mg g^{-1} h^{-1} in 2022 and 2023, respectively). The incomplete breakdown of proteins in the NC treatment was also evident from the foul odor emanating from the compost pile throughout the duration of the experiment. Similar findings were also reported by Raut *et al.* (2008).

3.3.5.4. Cellulase activity. Cellulases are enzymes that facilitate the breakdown of cellulose. Cellulose decomposition is the primary factor that restricts the quick generation of compost compared to other substrates (Raut *et al.*, 2008). The activity of cellulase relies on the specific types of cellulolytic microorganisms that colonize the organic waste (Goyal *et al.*, 2005; Ma *et al.*, 2019a). The results of this experiment suggest that there were differences in the trends of cellulase activity between the NC and RC treatments (Table 10). In the case of RC treatment, cellulose activity increased during the initial phases of the decomposition process, reaching its peak at 30 days (1.48, 1.56, and 1.52 mg g^{-1} h^{-1} in 2022, 2023, and mean value of two years, respectively), and then further decreased at 60 days (0.54, 0.62, and 0.58 mg g^{-1} h^{-1} in 2022, 2023, and mean value of two years, respectively) and 90 days (0.23, 0.20, and 0.22 mg g^{-1} h^{-1} in 2022, 2023, and mean value of two years, respectively) during both years. This high level of activity might have been caused by the initial inclusion of the microbial consortium containing cellulose-degrading bacteria (*Priestia megaterium* strain DBJ6 and *Micrococcus yunnanensis* strain DMB9) and fungi (*Aspergillus foetidus* strain DAJ2, *Trichoderma atrobrunnium* strain DTJ4, and *Phanerochaete chrysosporium* strain CBS129.27) in this treatment (Raut *et al.*, 2008). In contrast, in the NC treatment, cellulase activity continued to increase until the final day of the experiment (Table 10), suggesting that cellulose, the substrate material, remained available throughout the 90-day period. Initially, low cellulase activity in NC could be due to inadequate growth of cellulolytic microorganisms during the early composting phase, which subsequently increased in the later phase, leading to higher cellulase activity (Raut *et al.*, 2008). The difference in cellulase activity between RC and NC suggests that the microbial consortium introduced in the inoculated pile was potentially more effective in degrading cellulose compared to the native microorganisms in the control pile (Li *et al.*, 2020). These results are consistent with the findings reported by Goyal *et al.* (2005).

4. Conclusion

Groundnut haulm and shell in 3:1 proportion along with consortium culture was the best treatment combination for rapid composting. The effectiveness of rapid composting was evaluated by examining changes in different physical, chemical, and biological parameters (microbial populations and enzyme activities). The results clearly demonstrate that labile carbon and nitrogen present in the groundnut residues degraded 37.86 % more quickly during rapid composting compared to the traditional normal composting method. In contrast with the traditional composting method, rapid composting effectively shortened the composting duration to 90 days, as evidenced by improvements in different physico-chemical parameters such as C/N ratio, temperature, pH, total NPK, and moisture content. A significant decline in the C/N ratio, accompanied by an increase in total NPK values, indicated that the compost, generated from the rapid composting method, was of high quality when it reached maturity. The study of the microbial population dynamics at different phases of composting, along with the analysis of enzyme activities, provided a clearer understanding of the role of microorganisms and their metabolic processes throughout the composting process. Therefore, the microbial consortium containing potential cellulolytic strains developed in our laboratory and used in this work holds significant promise as a decomposer for *in situ* residue composting in agricultural fields. Further research in this area could open up new possibilities for sustainable and circular agriculture, effectively tackling the challenges of crop residue management.

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Research involving human participants and/or animals

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Consent for publication

All the authors gave their consent for publication of the results.

CRediT authorship contribution statement

Deblina Roy: Conceptualization, Methodology, Validation, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Sunil Kumar Gunri:** Conceptualization, Supervision, Formal analysis, Software, Validation, Writing – review & editing. **Champak Kumar Kundu:** Supervision, Data curation, Validation, Writing – review & editing. **Prasanta Kumar Bandyopadhyay:** Data curation, Validation, Writing – review & editing.

Declaration of competing interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data availability

Data will be made available on request.

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