To appear in: International Journal of Recycling of Organic Waste in Agriculture (IJROWA)
Online ISSN: 2251-7715 Print ISSN: 2195-3228

Received: 25 Feb 2024 Revised: 14 Apr 2024

Accepted: 13 Jun 2024

DOI: 10.57647/ijrowa-txnh-sf32

ORIGINAL RESEARCH

Enhancing nutrient-enriched compost through optimized co-composting of sugarcane bagasse in tropical environments

Suraj Asava[1], Dayanand Sharma[2]*, Chandrashekhar Parab[1], Rajnikant Prasad[1], Kunwar D Yadav[1]

[1]Department of Civil Engineering, SV National Institute of Technology, Surat, India 395007.

[2]Civil Engineering Department, Sharda University, Greater Noida, U.P., India 201310.

*Corresponding author email: *dayanandsvnit@gmail.com*

Abstract

Purpose: Improper sugarcane trash management, like burning or haphazard disposal, causes environmental pollution. Composting offers a sustainable solution in tropical environments, but challenges arise from its high C/N ratio and lignocellulose content, leading to longer processing times and nutrient deficiencies. This study evaluates co-composting sugarcane trash with indigenous materials to enhance efficiency and nutrient content, aiming to improve compost quality.

Methods: The research focuses on co-composting sugarcane bagasse with food waste, cow dung, and amritjal under optimal conditions. Material proportions were adjusted (Trial-1-3 and Control), and small bins were utilized to determine the ideal mix ratio. Monitoring over 56 days evaluated composting efficiency.

Results: Trial-2 peaked at 56℃ on day 11, while Trial-3 reached 51℃ on day 7. Control maintained lower temperatures. Ammoniacal nitrogen concentration varied, consistently higher in Trial-2. Total volatile solids decreased, indicating efficient decomposition, particularly in Trial-2. Composting resulted in a decrease in total organic carbon with an increase in ash content, nitrogen, potassium, and phosphorus. pH varied, with Trial-2 maintaining the highest. Electrical conductivity rose, while CO_2 production decreased over time. Moisture content exhibited variability, and germination indices improved in all trials, indicating compost maturity. C/N ratio decreased, and significant reductions in cellulose, hemicellulose, and lignin demonstrated effective decomposition.

Conclusion: Co-composting with food waste, cow dung, and amritjal, under optimized conditions, successfully transforms waste into a valuable agricultural resource, offering a sustainable solution for its management.

Keywords: Composting, Sugarcane, Food waste, C:N ratio, Germination index

Introduction

Globally, sugarcane is a crucial cash crop and a primary source for sugar production, with 1.87 billion tons produced worldwide in 2020, mostly in tropical areas, with Brazil, India, and China contributing 40%, 20%, and 6%, respectively (Pipitpukdee et al. 2020). In India alone, sugarcane cultivation covered 5.0 million hectares in 2020, yielding 392.80 million tons (Shukla et al. 2022). This cultivation results in significant sugarcane waste, with global production in 2012-2013 reaching 1.6 billion tons, generating 279 million tons of biomass residues, including bagasse and leaves (Chandel et al. 2012). The two main stages of sugarcane waste are agricultural and industrial, with an annual production of 10-12 tons per hectare of dry crop residues, often utilizing green leaves as fodder (Mishra and Yadav 2021). Open burning is a common practice among farmers worldwide due to labor scarcity and time constraints (Powar et al. 2022). At the industrial stage, waste such as press mud, bagasse, and spent wash is generated, with sugar factories commonly burning sugarcane residue for power generation, although it holds potential as a valuable feedstock for other goods (Rahayu et al. 2022).

Composting of sugarcane waste in tropical environments possess many opportunities and challenges. Tropical environments generally have higher temperatures and humidity compared to temperate regions. Higher temperatures can accelerate the composting process by speeding up microbial activity and decomposition of organic matter while higher humidity can provide the necessary moisture for composting (Azim et al. 2018). Tropical environments often have rich soil with high levels of organic matter and nutrients. Composting in such environments may result in nitrogen, phosphorus and potassium rich compost due to the abundance of organic materials available for decomposition (Craswell and Lefroy 2001). High carbon-to-nitrogen ratio and difficult to degrade lignocellulosic content in sugarcane waste are some of the challenges in its composting. Some researchers have investigated composting and co-composting of sugarcane trash (ST) using different methods and inoculants. The study by Ansari et al. (2021) reported that chemically pretreated bagasse significantly reduced its lignocellulosic content, transforming it into a humic substance with higher germination index percentages. Rahayu et al. (2022) highlighted the significant potential of lignocellulolytic bacterial consortia for decomposing sugarcane waste during processing. Additionally, Soto-Paz et al. (2021) revealed that processing time, mixing ratio variation, and turning frequency directly impact product quality. However, farmers may face difficulties in adopting pretreatments due to technological awareness limitations and financial constraints

(Powar et al. 2022). Previous studies have focused on composting individual components, supplemented with bulking agents to enhance the process, yet this approach presents challenges like secondary pollution and increased costs. Moreover, it may not effectively address the diverse agricultural wastes typical in rural areas. Hence, a multicomponent composting method is proposed, offering advantages such as increased efficiency in processing various agricultural wastes and yielding superior composting products due to their rich compositions (Bian et al. 2019). Nonetheless, there is a scarcity of studies on multi-component composting of ST.

The study introduces a novel approach by co-composting sugarcane trash (ST) with food waste (FW), cow dung (CD), and amritjal (AJ) to improve the efficiency of the composting process. Food waste contains fungi that facilitate the breakdown of recalcitrant compounds, while cow dung, with its abundant nitrogen content, is commonly co-composted with materials possessing lower nitrogen content for enhanced decomposition (Guo et al. 2022; Liu and Zhang 2023). Amritjal is a fermented organic liquid manure or soil conditioner made from locally available materials such as cow dung, cow urine and jaggery. It contains various beneficial micro-organisms, macro and micro-nutrients, plant growth promoters, antioxidant and plant protection properties (Biswas et al. 2023). The use of Amritjal directly as organic manure at large scale is challenging but it can be used as an inoculating agent in co-composting (Ravisankar et al. 2021). The study aims to experimentally evaluate the feasibility of co-composting FW and CD with sugarcane trash (ST) using various mixing ratios and inoculating with amritjal (AJ).

Materials and methods

Study area

The study was conducted at the Sardar Vallabhbhai National Institute of Technology (SVNIT), Solid Waste Laboratory, Surat from January to March 2020. The temperature at the site ranged from 22ºC to 32ºC with no rainfall.

Raw materials

1.5 tons of ST were collected from Shirdi, Gujarat, India, using local transport cargo and brought to the composting laboratory at SVNIT, Surat. Amritjal (AJ) was prepared at the laboratory by mixing 1 liter of cow urine, 50 grams of jaggery, 1 kg of cow dung, and 10 liters of water and kept for 4 days in a 15-liter bucket, covered with cloth, without contact with sunlight. The mixture was mixed daily 3 to 4 times clockwise and anticlockwise for 4 days until the AJ was ready for use. FW was collected from the three boy’s hostels of SVNIT and mixed together. Unwanted plastic materials were removed manually. Plastic drums were used to collect the food waste (FW). Fresh FW was ground using a churner, available in the mess, to reduce the particle size less than 1 mm, thereby enhancing degradation. Fresh CD was brought from a cow farm which is situated at Umragaon village near to SVNIT college campus. The Physicochemical characteristics of ST, FW, CD, and AJ are given in

Table 1.

Table 1. Characteristics of raw materials used during experiment.

Parameters	**ST**	**AJ**	**CD**	**FW**
Moisture Content (%)	46.38±4.01	98.86±0.95	85.10±4.14	87.46±3.89
pH	7.90±0.21	6.73±0.12	8.10±0.18	5.80±0.21
EC (mS/cm)	0.472±0.11	4.11±0.11	4.50±0.21	2.13±0.20
Volatile Solids (%)	84.60±3.89	16.76±1.84	65.66±2.92	76.28±2.98
Total Organic Carbon (%)	47.00±1.26	9.31±1.12	36.48±1.36	42.37±1.76
Nitrogen (%)	0.37±0.02	1.19±0.15	1.22±0.10	1.98±0.10
Phosphorous (%)	0.035±0.01	0.18±0.01	0.90±0.10	0.25±0.20
Potassium (%)	0.12±0.10	0.32±0.20	1.14±0.20	0.54±0.23

All values are mean of triplicates±standard deviation

ST= sugarcane trash, AJ= amritjal, CD= cow dung, FW= food waste, EC= electrical conductivity

Methodology

Composting was conducted in cylindrical plastic tubs with a capacity of 0.075 m^3, measuring 0.37 m in length and 0.51 m in diameter. These tubs were closed at the bottom and open at the top, allowing air to enter through the open top without external aeration. Additionally, a 10 mm hole was provided at the bottom of each tub for the removal of any generated leachate. Four combination trials of ST and co-composting materials were established: ST+AJ, ST+FW, ST+CD, and ST+W (control). The quantity of materials added was based on a wet weight basis, comprising 60% of the dry weight of ST, as optimal operational conditions were observed in this mixing ratio. All combinations of trials are listed below:

Trial 1 (ST+AJ) Sugarcane Trash (5.5 kg) + Amritjal (3.3 kg)
Trial 2 (ST +FW) Sugarcane Trash (5.5 kg) + Food waste (3.3 kg)
Trial 3 (ST +CD) Sugarcane Trash (5.5 kg) + Cow dung (3.3 kg)
Trial 4 (ST+W) (Control) Sugarcane Trash (5.5 kg) + Water (3.3 kg)

For each trial three replicates of plastic tubs were used. Each trial combination was mixed in a mechanical mixing vessel before putting in the tubs. Initial 7 days plastic tubs were covered with plastic sheets to avoid heat loss and the growth of fungi and bacteria. The mixture in plastic tubs were rotated after every 3 days from the 7th day to achieve sufficient mixing and agitation. The temperature was monitored every day by inserting probes at three different locations in a plastic tub i.e. top, middle and bottom and by taking its average. For other physicochemical parameters around 120 gram samples were collected from different parts of each reactor and then mixed to achieve homogeneity. The total duration of the composting experiment was 56 days. The overall methodology of this study has shown in Figure 1.

Figure 1. Flow diagram of sugarcane trash/ leaves collection to final conversion into compost

Analysis of physicochemical parameters

Standard methods for determination of physicochemical parameters were used as described in APHA (2023).Temperature was measured by using a Mextech ST9283B multi-stem thermometer. The temperature was measured at three points of the tub: the top surface, middle, and bottom. Subsequently, the average value was reported. To determine the moisture content, a known quantity of sample was oven dried at 70±2ºC for 24 hours and difference in weight was recorded. A 10-gram oven-dried sample was combined with distilled water at a ratio of 1:10 (w/v). The mixture was subsequently placed on a rotary shaker for two hours. The filtrate obtained through Whatman filter paper no. 42 was utilized to measure pH and electrical conductivity. The total nitrogen content was assessed using the Kjeldahl method. For the determination of ammoniacal nitrogen, the KCl extraction method was employed in conjunction with the phenate method. To calculate the total volatile solids, a known quantity of an oven-dried sample was placed into a muffle furnace set at 550±5ºC for 2 hours. The total organic carbon was determined by dividing the total volatile solids by a factor of 1.83 (Adhikari et al. 2009; Núñez et al. 2022). To calculate the CO_2 evolution rate, the soda lime method was utilized following the approach outlined by (Kalamdhad et al. 2008). For quantifying phosphorus content, the stannous chloride method was employed. This involved digesting a 0.2 gram sample with a mixture of H_2SO_4 and $HClO_4$ at a 5:1 ratio for 2 hours at 300°C. Potassium content was determined using a flame photometer (Jain et al. 2019). To compute the germination index (GI), a filtrate of 6 hours agitated mixture of sample and distilled water (5:10 w/v) was then placed into a Petri dish with tissue paper as medium. The germination index was calculated using equation (1) after 72 hours of incubation at 25 ºC. Distilled water was used in control (Yang et al. 2021).

$$\text{Relative seed germination (\%)} = \frac{\text{Number of seeds germinated extra} \times 100}{\text{Number of seeds germinated in control}}$$

$$\text{GI (\%)} = \frac{(\text{Relative seed germination}) \times (\text{Relative root growth})}{100} \times 10 \qquad (1)$$

To determine the lignin concentration, a powdered sample weighing 3 grams was digested with 72% H_2SO_4. The resulting extract was then filtered, and its absorbance at 205 nm was measured. Subsequently, the sample was filtered again, and the filtrate was dried at 105°C, following the procedure outlined by the National Renewable Energy Laboratory. To determine the cellulose content, the method of acetic/nitric reagent extraction, as described by Updegraff (1969). For assessing hemicellulose content, the approach involved utilizing the variance between natural detergent fiber (NDF) and acid detergent fiber (ADF) (Holtzapple 2003).

Statistical analysis

Significance of variations among all physico-chemical and biological parameters was calculated using one-way Analysis of Variance (ANOVA) at a level of significance less than 0.05 (p <0.05). For the computation of variance, SPSS 13.0 software was utilized.

Results and discussions

Variation of compost temperature

Higher ambient temperatures enhance composting efficiency by raising pile temperature, essential for pathogen and weed seed elimination (Khater 2016; Budihardjo et al. 2018). Figure 2 illustrates the temporal variations of temperature in compost trials 1-3 and the control. The variation among the treatments was significant (p<0.05) (Table S1). Trial-1 initiated at 38°C, reaching the thermophilic phase at 47°C by day 7, lasting 9 days. Trial-2 and 3 also entered the thermophilic phase on day 2 at 37°C and 32°C, respectively. Trial-2 peaked at 56°C on day 11, lasting 20 days, while Trial-3 peaked at 51°C on day 7, lasting 16 days. The control started at 30°C, reaching 37°C on day 2, with a maximum temperature of 37°C. NH_4^+-N levels rose with temperature, indicating mesophilic to thermophilic transition. After 56 days, temperatures stabilized around 32°C, 30°C, 32°C, and 31°C for Trial-1-4 respectively matching with the ambient temperature which shows the attainment of maturity.

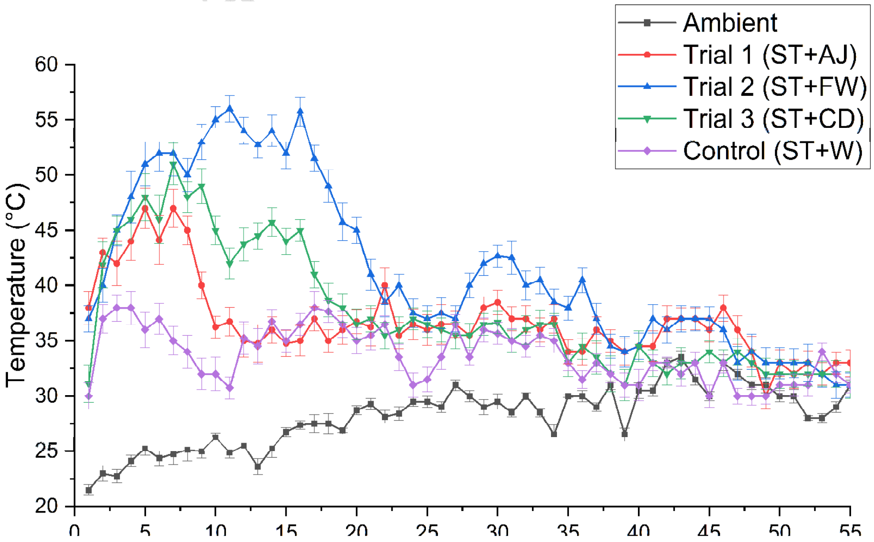

Figure 2. Temporal variations of Temperature.

Variations of moisture content, pH, electrical conductivity and CO_2 evolution rate

Compost stability and greenhouse gas emissions are significantly impacted by moisture content (MC) manipulation and 55-60% considered as an optimum MC (Gurusamy et al. 2021; Ermolaev et al. 2019). Trial-2 begins with the highest MC (76±2%), followed by Trial-1 at 74±3.5%, while Control and Trial-3 have intermediate initial MC of 72% and 73%, respectively. Over 56 days, Trial-3 consistently decreases in MC to a final level of 53%, whereas Trial-2 maintains high MC throughout, and Trial-1 shows a less pronounced decrease. Control exhibits fluctuations but generally maintains moderate MC. Both Control and Trial-3 display lower variability in MC, while Trial-2 shows moderate variability, and Trial-1 exhibits variability, particularly at the beginning and end stages as depicted in Figure 3a. However, not significant variation in MC was observed among all treatments ($p>0.05$) (Table S1).

The pH level significantly influences microbial respiration and degradation rates in composting, with alkaline pH crucial for maturity and stability evaluation, while acidic pH can impede microbial activity and degrade rates. Trial-1 started at pH 7.2, dropping to 6.8 after three days, ending at pH 7.2 after 56 days, while Trial-2 and Trial-3 reached pH levels of 5.4 and 6.4, respectively (Figure 3b), but the difference was not significant ($p<0.05$) (Table S1). The control maintained a pH of 6.7. Trial-2 peaked at pH 7.1 on day 21, while Trial-3 increased from 6.4 to 7.5 within two days, reaching a final pH of 7.6. The control maintained a stable pH, consistent with Sharma et al. (2018).

Electrical conductivity (EC) reflects concentration of salts generated during composting. Trial-2 began with the highest EC (3.3±0.009 mS/cm), indicating a higher concentration of dissolved salts, while Control had the lowest initial EC (2.2±0.002 mS/cm). Throughout the period, Trial-3 and Trial-2 consistently showed EC increases (4.3±0.006 mS/cm) and (4.2±0.004 mS/cm). Although Trial-1 and Control also experienced rises, their rates were slower. Trial-2 and Trial-3 exhibited higher EC variability, suggesting fluctuating dissolved salt concentrations, while Control and Trial-1 showed lower variability. Overall, EC tended to rise over time significantly ($p<0.05$) (Table S1), indicating salt accumulation during composting (Figure 3c).

Significant variation of CO_2 production rate among all treatments was observed ($p<0.05$) (Table S1) as shown in Figure 3d. Trial-2 consistently shows the highest CO_2 production rates throughout the 56 days (22.12±0.7 mg/gVS/day). Trial-3 also maintains relatively high CO_2 production, especially in the early stages while Trial-1 and Control have lower CO_2 production rates. Trial-2 and Trial-3 have relatively low variability in CO_2 production, indicating consistent rates. Control exhibits variability, especially in the later stages. CO_2 production generally decreases over the 56 days in all trials. Trial-2 and Trial-3 maintain higher production rates even at the later stages. The decrease in CO_2 production over time may suggest a reduction in microbial activity or the availability of organic material for decomposition.

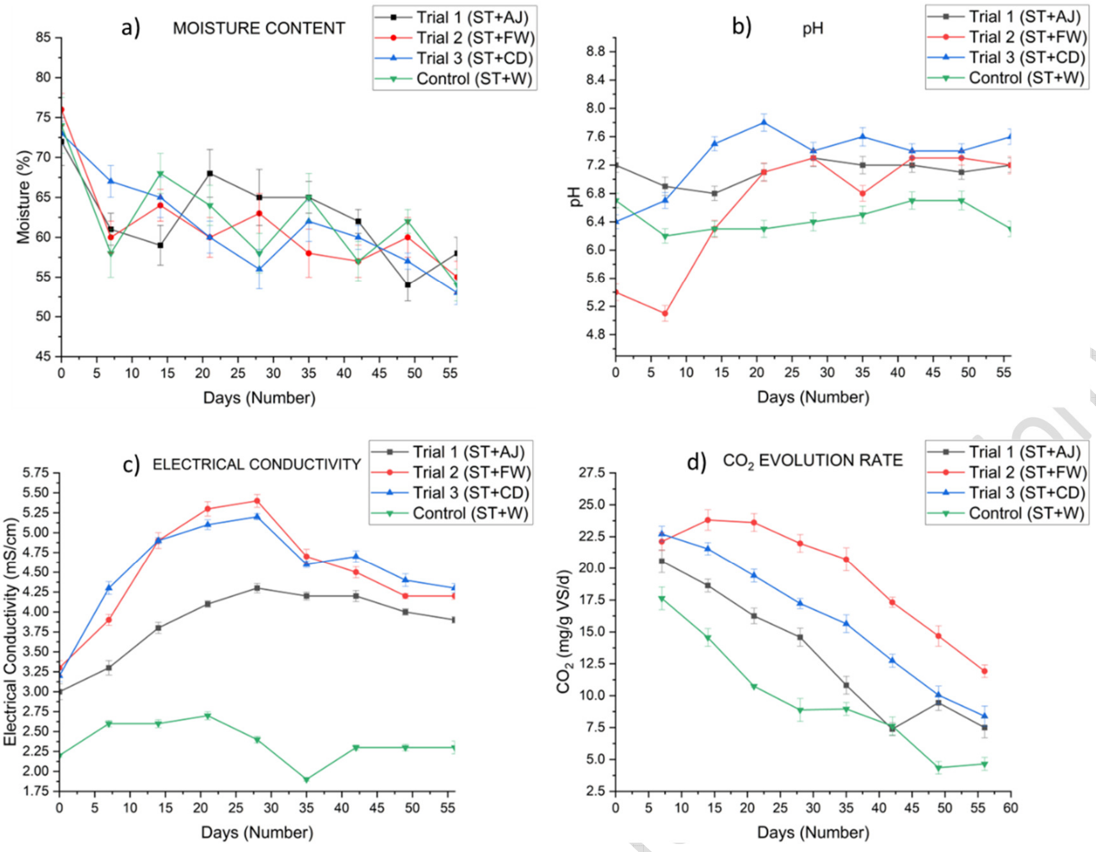

Figure 3. Temporal variations of a) Moisture b) pH c) Electrical Conductivity and d) CO_2 production rate.

Variations of total volatile solids, total organic carbon, ash content and ammoniacal nitrogen

Total volatile solids (TVS) are a vital parameter in composting, indicating the organic matter content, excluding carbon-based inert like plastic, and measured by its combustion at high temperatures (Kumar et al. 2010). TVS reduction during composting influences physical, chemical, and biological properties, indicating the organic matter's decomposition. Trial-2 starts with the highest %TVS (83.8 ± 2.1%), followed by Control and Trial-1 with relatively high initial %TVS values (82.54 ± 1.2% and 82.4 ± 1.8%). Over 56 days, %TVS generally decreases across all trials, showing volatile solids loss. Significant variation was observed in TVS among all treatments ($p<0.05$) (Table S1). Moderate variability is observed in Trial-2 and Trial-3, suggesting organic matter breakdown during composting (Figure 4a).

Total organic carbon (TOC) within soil organic matter significantly impacts soil characteristics vital for plant growth and soil health, encompassing color, nutrient retention, turnover, and stability (Murphy 2015). Trial-2 commences with the highest %TOC (46.56±1.17%), followed by Control and Trial-1 with relatively high initial %TOC values (45.86±0.67%). Over 56 days, %TOC generally declines across all trials (30.72%, 26.72%, 29.28%, and 34.08%, respectively), indicating organic carbon decomposition during composting. Trial-2 maintains a relatively higher %TOC (34.08%) compared to others, while Control and Trial-1 exhibit lower %TOC variability. Significant variation was observed among all treatments ($p<0.05$) (Table S1). Moderate variability was observed in Trial-2 and Trial-3. The decreasing TOC trend denotes organic carbon breakdown during composting (Figure 4b).

The ash content in compost indicates both mineral elements and organic matter, representing the non-volatile mineral component crucial for understanding compost composition (Dědina et al. 2022). It offers insights into nutrient availability and the compost's impact on soil health and plant growth. Trial-3 begins with the highest ash content at 20.1%, suggesting a greater initial inorganic material proportion, with Trial-1 and Control also exhibiting relatively high initial ash content at 17.47% and 17.6%, respectively. Over 56 days, ash content significantly increases across all trials ($p<0.05$) (Table S1), with Trial-2 maintaining relatively higher ash content. Trial-2 and Trial-3 show higher ash content variability, while Control and Trial-1 display moderate variability. The increasing trend in ash content indicates mineral and inorganic material accumulation during composting (Figure 4c).

Ammoniacal Nitrogen (NH_3–N) is crucial in composting for decomposition and compost quality. It facilitates nitrogen's return to the soil, benefiting plant growth and soil health by converting nitrogen into a usable form (Sharma et al. 2022). Trial-2 starts at 152 mg/L NH_3–N, Control at 157 mg/L, Trial-1 at 147 mg/L, and Trial-3 at 149 mg/L. NH_3–N concentrations fluctuate over 56 days in all trials, with Trial-2 consistently higher and exhibiting higher variability. Control shows relatively lower variability. These fluctuations reflect dynamic microbial activity and nitrogen transformations during composting (Figure 4d).

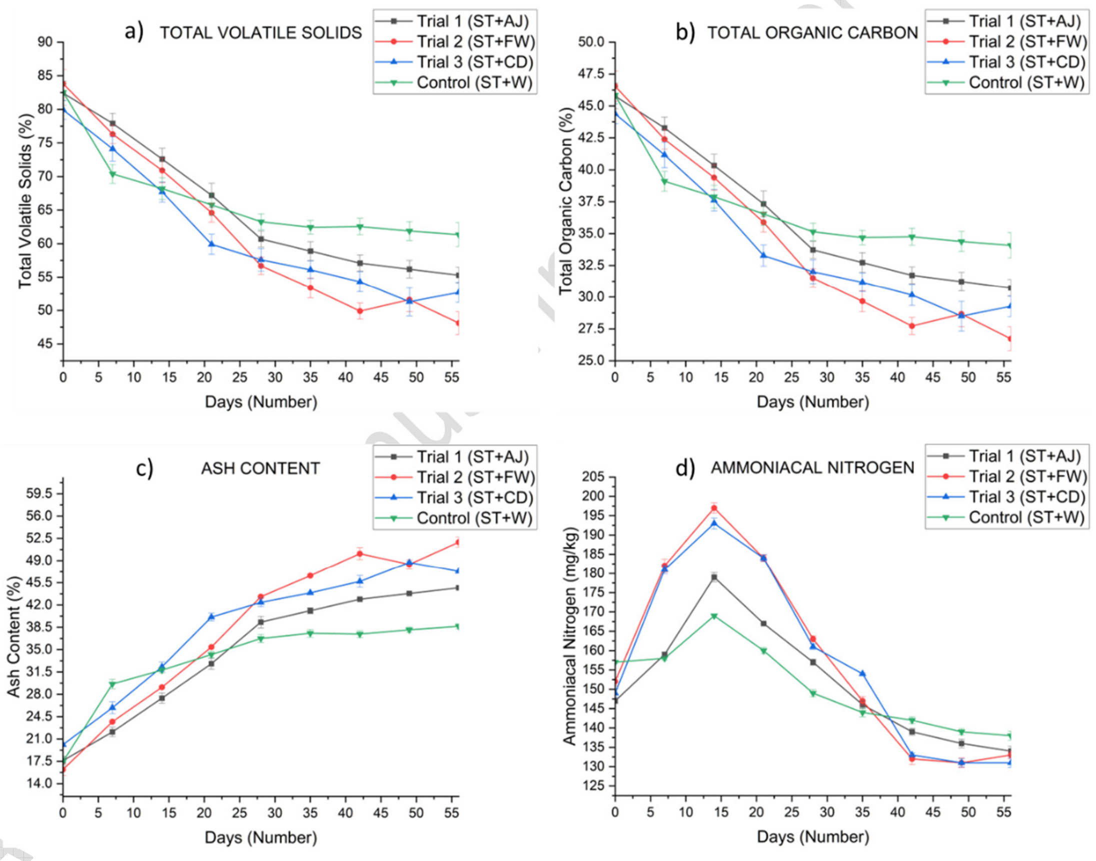

Figure 4. Temporal variations of a) Total Volatile Solids b) Total Organic Carbon c) Ash content and d) Ammoniacal Nitrogen

Variations of total nitrogen, C/N ratio, phosphorous and potassium

As a measure of the nutrient richness of the compost, the total nitrogen (TN) concentration is important during the composting process (Sayara et al. 2020). Organic matter breaks down more quickly when there is enough nitrogen present to encourage microbial activity. Trial-2 starts with the highest concentration of TN 1.92%, while Control starts with the lowest concentration of 0.3%. Trial-1 and Trial-3 have lower initial concentrations of 1.54% and 1.64% respectively. TN concentrations generally show a rise over 0 to 35 days in all trials. Trial-2 consistently maintains higher concentrations compared to other trials. Control shows relatively lower variability. A significant rise in TN concentrations among all treatments ($p<0.05$) (Table S1) was observed as depicted in Figure 5a indicates microbial metabolism of proteins (Raj and Antil 2011).

Carbon to nitrogen ratio (C/N ratio), often between 25 and 30:1, encourages the proliferation of microorganisms and aids in the breakdown of organic matter into stable humus (Eiland et al. 2001). Figure 5b shows C/N ratio variation among all treatments ($p<0.05$) (Table S1), with Control having the highest ratio of 152.85, compared to Trial-1, Trial-2, and Trial-3 with ratios of 29.73, 24.12, and 27.07, respectively. Control's high C/N ratio was due to ST's high fibre content, lacking nitrogen sources (Cifuentes et al. 2013). Trial-1, Trial-2, and Trial-3 show substantial C/N ratio decreases up to 35 days, stabilizing thereafter. Trial-2 has the most significant decrease due to the ability of FW to foster fungus growth, efficiently degrading lignocellulosic materials with less nitrogen dependency Singh et al. (2008). Control's ratio does not decrease substantially due to minimal microbial activity absence (Naher et al. 2018; Singh et al. 2008).

During composting, organic material breakdown increases phosphorus levels as microorganisms utilize phosphorus for metabolism, and plants absorb it, particularly in the form of hydrogen phosphate ions (Mishra and Yadav 2021; Sharma and Yadav 2017). As organic matter breaks down, there's a greater carbon loss, potentially contributing to phosphorus concentration rise during composting. Significant variation was observed in phosphorus content among all treatments ($p<0.05$) (Table S1) during composting. Initially, Trial-3 had the highest phosphorus at 1.37 g/kg, followed by Trial-2 at 1.18 g/kg and Trial-1 at 1.09 g/kg, eventually increasing to 3.31 g/kg, 2.62 g/kg, and 2.39 g/kg, respectively. Similarly, the Control started at 0.98 g/kg and rose to 2.04 g/kg, the lowest compared to Trials-1, 2, and 3 (Figure 5c). Trial-3's higher increase suggests compost as a significant phosphorus source.

The initial concentrations of potassium in Trail-1, Trial-2, Trial-3 and control are 4.4, 4.7, 4.7 and 2.2 (g/kg) respectively, increased significantly ($p<0.05$) (Table S1) to 6.5, 7.4, 8.5 and 3.38 (g/kg) respectively, at end 56 days composting period (Figure 5d). Trial-3 has the highest increase in potassium content which may be due to initial higher concentration of potassium in CD as compared to FW and AJ. Microbes absorption and immobilization of potassium was partially responsible for the rise in potassium concentration in all of the trials.

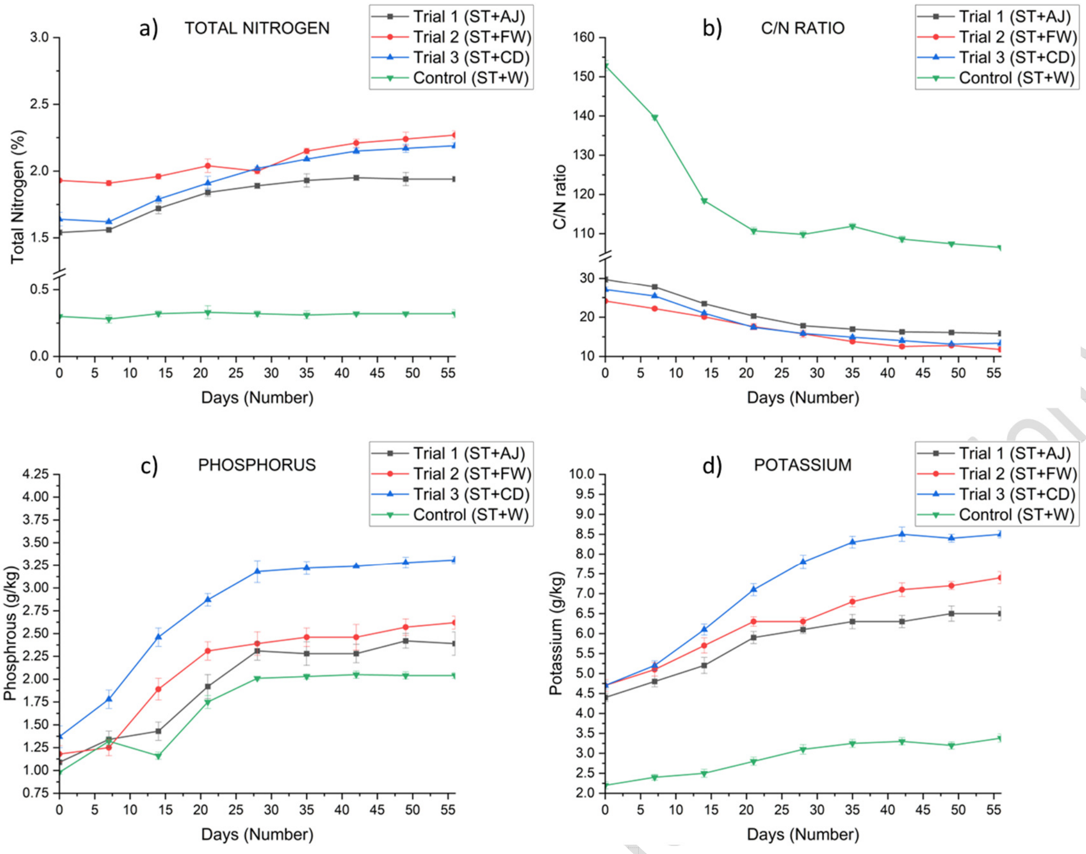

Figure 5. Temporal variations of a) Total Nitrogen b) C/N Ratio c) Phosphorus and d) Potassium

Variations of cellulose, hemicellulose, lignin and germination index

Cellulose, present in various organic compounds like plant residues, structures plant cell walls, and acts as a key carbon source in composting (Eklind and Kirchmann 2000). Figure 6a, illustrates cellulose's temporal variation significant across all trials ($p<0.05$) (Table S1), with Trial-2 showing the most significant decrease, dropping by 30.3% from the initial 41.7%. Following Trial-1, Trial-3 experiences a decrease from 41.7% to 32.1%. Compared to Trial-2 and Trial-3, Trial-1 and Control exhibit lesser reductions, possibly due to FW and CD's higher capacity to foster fungi and bacteria for organic matter decomposition. Cellulose reduction was more pronounced in trials with increased availability of hemicellulose compounds alongside cow dung, compost, and food waste (Mishra and Yadav 2021).

The complex carbohydrate polymer hemicellulose, comprising 25% to 30% of the total dry weight, serves as an energy source for microorganisms during the composting, with its degradation occurring more rapidly than that of cellulose as the temperatures rise (Mishra and Yadav 2021). Figure 6b, illustrates the temporal variation of hemicellulose across all trials which was significantly different ($p<0.05$) (Table S1), with Trial-2 and Trial-3 experiencing a more substantial reduction in hemicellulose content from 33.4% to 20.3% and 33.7% to 23.7%, respectively. Trial-1 demonstrates a reduction from 35.7% to 27.1%, surpassing that of the Control. The maximum rate of hemicellulose degradation was observed within the initial 28 days across all trials, except for the Control.

The structure of lignin is extremely complex and resistant to microbial degradation (Kamimura et al. 2019). Lignin content undergoes significant reduction primarily during the thermophilic phase, aided by the action of various microorganisms. Figure 6c depicts the temporal variation of lignin across all trials. Microbial inoculants containing fungi, particularly during the thermophilic phase, play a crucial role in breaking down resilient substances like lignin (Tuomela et al. 2000). Although the variation in lignin content among all treatments was not significant ($p>0.05$) (Table S1), Trial-2 achieves a higher reduction from 13.97% to 8.86% compared to Trial-3 from 13.6% to 9.81% and Trial-1 from 13.73% to 10.54%. Maximum reduction occurs between 7 to 35 days, the thermophilic phase, in all trials except the Control.

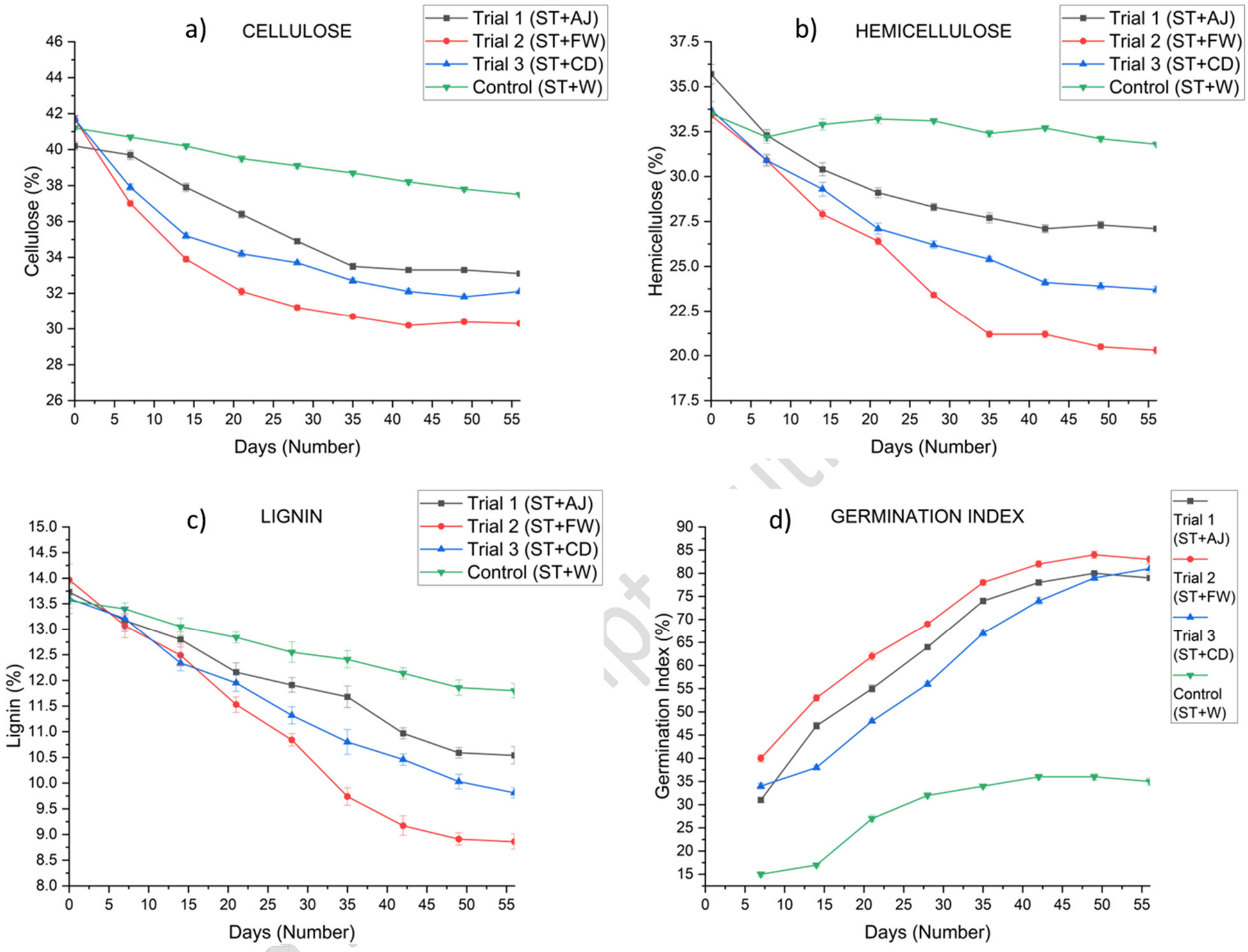

Figure 6. Temporal variations of a) Cellulose b) Hemicellulose c) Lignin and d) Germination Index

In composting, the germination index (GI) indicates phytotoxicity and compost's impact on plant growth (Naher et al. 2018). A high index suggests compost suitability without hindering seed germination or early plant growth. According to Mishra and Yadav (2021), a GI exceeding 80% indicates compost that is free from toxins, stable, and mature. Naher et al. (2018) suggest values from 50% to 80% as safe. Figure 6d shows GI changes which were significant ($p<0.05$) (Table S1) across trials. Initially, Trial-1, 2, 3, and Control had indexes of 31±0.56%, 40±0.77%, 34±0.61%, and 15±0.54%, rising to 79±0.58%, 83±0.76%, 81±0.91%, and 35±0.81%, indicating compost maturity. Values exceeding 80% indicate suitability for agriculture, with all trials except the control being suitable for soil. Trial-2 exhibited the highest germination rate, followed by Trial-3 and Trial-1, suggesting a more rapid elimination of phytotoxic compounds. Compost maturity parameters after 45 days of composting are shown in

Table along with the standards given by The Fertilizer Association of India (FAI 2007), The Test Method for the Examination of Composting and Compost (TMECC 2002) (Refer Table 2).

Table 2. Compost Maturity Parameters with FAI (2007), TMECC (2002) standards

Name of Parameters	Trial 1 (ST+AJ)	Trial 2 (ST+FW)	Trial 3 (ST+CD)	Control (ST+W)	FAI (2007)	TMECC (2002)
Moisture (%)	58±2.00	55±2.00	53±1.50	54±2.00	35-55	35-45
pH	7.20±0.10	7.20±0.12	7.60±0.11	6.30±0.11	6.5-8.5	5.5-8.5
Electrical Conductivity (mS/cm)	3.90±0.04	4.20±0.04	4.30±0.06	2.30±0.08	2-6	≥ 4
Total Volatile Solids (%)	55.30±1.20	48.10±1.70	52.70±1.5	61.34±1.80	-	-
Total Organic Carbon (%)	30.72±0.67	26.72±0.94	29.28±0.83	34.08±1.00	≥16	-
Total Nitrogen (%)	1.94±0.02	2.27±0.03	2.19±0.02	0.32±0.03	1.0-3.0	-
Carbon/Nitrogen Ratio	15.84±0.70	11.77±0.70	13.37±0.80	106.49±0.30	< 25	≤ 25
Phosphorus (g/kg)	2.39±0.13	2.62±0.07	3.31±0.04	2.04±0.03	0.4-1.1	-
Potassium (g/kg)	6.50±0.17	7.40±0.15	8.5±0.09	3.38±0.10	0.6-1.7	≥ 4
Hemicellulose (%)	27.10±0.15	20.30±0.20	23.70±0.20	31.80±0.11	-	-
Cellulose (%)	33.10±0.09	26.30 ±0.08	32.10±0.07	37.50±0.11	-	-
Lignin (%)	10.54±0.17	8.86±0.15	9.81±0.10	11.8±0.14	-	-
Germination Index (%)	79±0.58	83±0.76	81±0.91	35±0.81	-	-

All values are mean of triplicates±standard deviation

Conclusion

The addition of co-composting materials such as amritjal, food waste, and cow dung with sugarcane trash improved the composting process compared to the control. From the physico-chemical analysis, Trial-2 (ST+FW) showed better results compared to other trials. Trial-2 achieved a maximum temperature of 56°C on day 11 and lasted for 20 days in the thermophilic phase. It also maintained high moisture content throughout the process compared to other trials. The CO_2 evolution rate of Trial-2 was highest at 23.81 mg/gVS/day on the 14th day of composting, showing a high rate of microbial activity. Trial-2 combination observed the highest reduction in organic matter, i.e., 42.60%, and ash content increased by more than 200%. In terms of nutrient availability, Trail-2 compost had the highest nitrogen content of 2.27%, whereas Trial-3 (ST+CD) compost showed the highest concentration of phosphorus and potassium, i.e., 3.31 g/kg and 8.5 g/kg, respectively. Trail-2 showed the maximum reduction in cellulose, hemicellulose, and lignin by 27.33%, 29.67%, and 36.57%, respectively. The germination index of Trail-2 was the highest at 83%, indicating that the compost was most suitable as organic manure compared to other trials.

Acknowledgments: Authors are thankful for the laboratory facility provided by the Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology, Surat.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest: The authors declare that there are no conflicts of interest associated with this study.

Author contribution: All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

References

Adhikari BK, Barrington S, Martinez J, King S (2009) Effectiveness of three bulking agents for food waste composting. Waste Manag 29:197–203. https://doi.org/10.1016/j.wasman.2008.04.001

Ansari M, Zafar U, Ejaz U, et al (2021) Comparison of composting of chemically pretreated and fermented sugarcane bagasse for zero-waste biorefinery. J Mater Cycles Waste Manag 23:911–921. https://doi.org/10.1007/s10163-021-01176-w

APHA, American Public Health Association, American Water Works Association, Federation WE (2023) Standard Methods for the Examination of Water and Wastewater 24th ed. Lipps WC, Braun-Howland EB, Baxter TE, eds.

Azim K, Soudi B, Boukhari S, et al (2018) Composting parameters and compost quality: a literature review. Org Agric 8:141–158. https://doi.org/10.1007/s13165-017-0180-z

Bian B, Hu X, Zhang S, et al (2019) Pilot-scale composting of typical multiple agricultural wastes: Parameter optimization and mechanisms. Bioresour Technol 287:121482. https://doi.org/10.1016/j.biortech.2019.121482

Biswas S, Das R, Thakur R (2023) Effect of corm and soil treatments with organic liquid formulations on performance of elephant foot yam in Jharkhand, India. Int J Plant Soil Sci 35:116–124. https://doi.org/10.9734/ijpss/2023/v35i52827

Budihardjo MA, Sutrisno E, Purwono, Fatimah M (2018) Leaves composting process and the influence of rumen content and bran addition. MATEC Web Conf 159:1–4. https://doi.org/10.1051/matecconf/201815901033

Chandel AK, Silva S, Singh OV (2012) Sugarcane bagasse and leaves : Foreseeable biomass of biofuel and bio-products. 11–20. https://doi.org/10.1002/jctb.2742

Cifuentes R, de León R, Porres C, Rolz C (2013) Windrow composting of waste sugar cane and press mud mixtures. Sugar Tech 15:406–411. https://doi.org/10.1007/s12355-013-0217-x

Craswell ET, Lefroy RDB (2001) The role and function of organic matter in tropical soils. Nutr Cycl Agroecosystems 61:7–18. https://doi.org/10.1023/A:1013656024633

Dědina M, Jarošíková A, Plíva P, Dubský M (2022) The effect of ash admixture on compost quality and availability of nutrients. Sustain 14. https://doi.org/10.3390/su14031640

Eiland F, Klamer M, Lind A-M, et al (2001) Influence of initial C/N ratio on chemical and microbial composition during long term composting of straw. Microb Ecol 41:272–280. https://doi.org/10.1007/s002480000071

Eklind Y, Kirchmann H (2000) Composting and storage of organic household waste with different litter amendments. I: Carbon turnover. Bioresour Technol 74:115–124. https://doi.org/https://doi.org/10.1016/S0960-8524(00)00004-3

Ermolaev E, Sundberg C, Pell M, et al (2019) Effects of moisture on emissions of methane, nitrous oxide and carbon dioxide from food and garden waste composting. J Clean Prod 240. https://doi.org/10.1016/j.jclepro.2019.118165

FAI (2007) The Fertiliser (Control) Order 1985. The Fertiliser Association of India, 10, Shaheed Jit Singh Marg, New Delhi, India

Guo H nan, Liu H tao, Wu S (2022) Immobilization pathways of heavy metals in composting: Interactions of microbial community and functional gene under varying C/N ratios and bulking agents. J Hazard Mater 426:128103. https://doi.org/10.1016/j.jhazmat.2021.128103

Gurusamy NN, Puffer N, de Jongh C, et al (2021) Effect of initial moisture content and sample storage duration on compost stability using the ORG0020 dynamic respiration test. Waste Manag 125:215–219. https://doi.org/10.1016/j.wasman.2021.02.048

Holtzapple MT (2003) HEMICELLULOSES. In: Caballero BBT-E of FS and N (Second E (ed). Academic Press, Oxford, pp 3060–3071

Jain MS, Daga M, Kalamdhad AS (2019) Variation in the key indicators during composting of municipal solid organic wastes. Sustain Environ Res 1:1–8. https://doi.org/10.1186/s42834-019-0012-9

Kalamdhad AS, Pasha M, Kazmi AA (2008) Stability evaluation of compost by respiration techniques in a rotary drum composter. Resour Conserv Recycl 52:829–834. https://doi.org/10.1016/j.resconrec.2007.12.003

Kamimura N, Sakamoto S, Mitsuda N, et al (2019) Advances in microbial lignin degradation and its applications. Curr Opin Biotechnol 56:179–186. https://doi.org/10.1016/j.copbio.2018.11.011

Khater E-SG (2016) Effect of ambient temperature and air flow rate on the temperature inside the compost pile. Misr J Agric Eng 33:1017–1032. https://doi.org/10.21608/mjae.2016.97790

Kumar M, Ou Y, Lin J (2010) Co-composting of green waste and food waste at low C / N ratio. Waste Manag 30:602–609. https://doi.org/10.1016/j.wasman.2009.11.023

Liu X, Zhang L (2023) Bioresource technology effects of additives on the co-composting of forest residues with cattle manure. Bioresour Technol 368:128384. https://doi.org/10.1016/j.biortech.2022.128384

Mishra SK, Yadav KD (2021) Disposal of garden waste using food waste inoculant in rotary drums and their ranking using analytical hierarchy process. Bioresour Technol Reports 15:100710. https://doi.org/10.1016/j.biteb.2021.100710

Murphy BW (2015) Impact of soil organic matter on soil properties—a review with emphasis on Australian soils. Soil Res 53:605–635. https://doi.org/10.1071/SR14246

Naher UA, Sarkar MIU, Jahan A, Biswas JC (2018) Co-composting urban waste, plant residues, and rock Phosphate: Biochemical characterization and evaluation of compost maturity. Commun Soil Sci Plant Anal 49:751–762. https://doi.org/10.1080/00103624.2018.1435799

Núñez F, Fernando L, Fernández L, et al (2022) Effect of the mixing ratio on the composting of OFMSW digestate : Assessment of compost quality Total Kjeldahl Nitrogen. J Mater Cycles Waste Manag 24:1818–1831. https://doi.org/10.1007/s10163-022-01438-1

Pipitpukdee S, Attavanich W, Bejranonda S (2020) Climate change impacts on sugarcane production in Thailand. Atmosphere (Basel) 11:1–15. https://doi.org/10.3390/ATMOS11040408

Powar R V, Mehetre SA, Powar TR, Patil SB (2022) End-use applications of sugarcane trash: A comprehensive review. Sugar Tech 24:699–714. https://doi.org/10.1007/s12355-022-01107-5

Rahayu F, Nugraheni SD, Diana NE, et al (2022) The potential of new bio-decomposers for composting sugarcane waste. IOP Conf Ser Earth Environ Sci 974. https://doi.org/10.1088/1755-1315/974/1/012060

Raj D, Antil RS (2011) Evaluation of maturity and stability parameters of composts prepared from agro-industrial wastes. Bioresour Technol 102:2868–2873. https://doi.org/10.1016/j.biortech.2010.10.077

Ravisankar N, Ansari MA, Panwar AS, et al (2021) Organic farming research in India: Potential technologies and way forward. Indian J Agron 66:142–162. http://krishi.icar.gov.in/jspui/handle/123456789/74580

Sayara T, Basheer-Salimia R, Hawamde F, Sánchez A (2020) Recycling of organic wastes through composting: Process performance and compost application in agriculture. Agronomy 10. https://doi.org/10.3390/agronomy10111838

Sharma D, Prasad R, Patel B, and Parashar CK (2022) Biotransformation of sludges from dairy and sugarcane industries through vermicomposting using the epigeic earthworm Eisenia fetida. Int J Recycl Org Waste Agricul 11:165-175. https://dx.doi.org/10.30486/ijrowa.2021.1922034.1196

Sharma D, Yadav KD (2017) Bioconversion of flowers waste: Composing using dry leaves as bulking agent. Environ Eng Res 22:237–244. https://doi.org/10.4491/eer.2016.126

Sharma D, Yadav KD, Kumar S (2018) Biotransformation of flower waste composting: Optimization of waste combinations using response surface methodology. Bioresour Technol 270:198–207. https://doi.org/10.1016/j.biortech.2018.09.036

Shukla SK, Sharma L, Jaiswal VP, et al (2022) Diversification options in sugarcane-based cropping systems for doubling farmers' income in subtropical India. Sugar Tech 24:1212–1229. https://doi.org/10.1007/s12355-022-01127-1

Singh P, Suman A, Tiwari P, et al (2008) Biological pretreatment of sugarcane trash for its conversion to fermentable sugars. World J Microbiol Biotechnol 24:667–673. https://doi.org/10.1007/s11274-007-9522-4

Soto-Paz J, Gea T, Alfonso-Morales W, et al (2021) Co-composting of Biowaste: Simultaneous optimization of the process and final product quality using simulation and optimisation tools. Waste Biomass Valorization 12:4489–4502. https://doi.org/10.1007/s12649-020-01321-w

TMECC (2002) Test Methods for the Examination of Composting and Compost. USDA and US. Composting Council, Bethesda, MD

Tuomela M, Vikman M, Hatakka A, Itävaara M (2000) Biodegradation of lignin in a compost environment: A review. Bioresour Technol 72:169–183. https://doi.org/https://doi.org/10.1016/S0960-8524(99)00104-2

Updegraff DM (1969) Semimicro determination of cellulose in biological materials. Anal Biochem 32:420–424. https://doi.org/10.1016/S0003-2697(69)80009-6

Yang Y, Wang G, Li G, et al (2021) Selection of sensitive seeds for evaluation of compost maturity with the seed germination index. Waste Manag 136:238–243. https://doi.org/10.1016/j.wasman.2021.09.037

Supplementary material

Table S2. One-way ANOVA of physicochemical parameters

Parameters	Source of variation	Sum of squares	Degree of freedom	Mean square	F-value	P-value
Temperature	Between Groups	1678.715	3	559.572	20.606	0.000*
	Within Groups	5974.175	220	27.155		
	Total	7652.890	223			
Moisture content	Between Groups	18.571	3	6.190	0.063	0.979**
	Within Groups	5128.857	52	98.632		
	Total	5147.429	55			
pH	Between Groups	1.227	3	0.409	1.766	0.165**
	Within Groups	12.041	52	0.232		
	Total	13.269	55			
Electrical conductivity	Between Groups	43.871	3	14.624	73.523	0.000*
	Within Groups	10.343	52	0.199		
	Total	54.214	55			
CO2 evolution rate	Between Groups	362.721	3	120.907	3.571	0.021*
	Within Groups	1625.316	48	33.861		
	Total	1988.038	51			
Total volatile solids	Between Groups	1043.821	3	347.940	2.821	0.048*
	Within Groups	6413.539	52	123.337		
	Total	7457.360	55			
Total organic carbon	Between Groups	322.124	3	107.375	2.821	0.048*
	Within Groups	1979.486	52	38.067		
	Total	2301.610	55			
Ash content	Between Groups	1043.821	3	347.940	2.821	0.048*
	Within Groups	6413.539	52	123.337		
	Total	7457.360	55			
Ammoniacal nitrogen	Between Groups	1030.143	3	343.381	1.770	0.164**
	Within Groups	10089.857	52	194.036		
	Total	11120.000	55			
Total nitrogen	Between Groups	30.164	3	10.055	552.968	0.000*
	Within Groups	0.946	52	0.018		
	Total	31.110	55			
C/N ratio	Between Groups	55757.992	3	18585.997	462.375	0.000*
	Within Groups	2090.232	52	40.197		
	Total	57848.224	55			
Phosphorous	Between Groups	11.332	3	3.777	8.600	0.000*
	Within Groups	22.839	52	0.439		
	Total	34.171	55			
Potassium	Between Groups	92.265	3	30.755	31.171	0.000*
	Within Groups	31.573	32	0.987		
	Total	123.838	35			
Hemicellulose	Between Groups	288.678	3	96.226	8.609	0.000*
	Within Groups	357.682	32	11.178		
	Total	646.360	35			
Cellulose	Between Groups	184.856	3	61.619	6.824	0.001*

	Within Groups	288.960	32	9.030		
	Total	473.816	35			
Lignin	Between Groups	13.487	3	4.496	2.484	0.079**
	Within Groups	57.911	32	1.810		
	Total	71.398	35			
Germination index	Between Groups	7695.250	3	2565.083	10.366	0.000*
	Within Groups	6928.750	28	247.455		
	Total	14624.000	31			

*Significant difference between the means of all trials ($p<0.05$)
**No significant difference between the means of all trials ($p>0.05$)