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RESEARCH ARTICLE

Bioconversion of coir ETP sludge: An eco-friendly path to circular economy

Puthan Ravindranath Divya[1], Karuppusamy Sivasubramanian[1*], Muthunalliappan Maheswari[1], Kaliappan Sathiya Bama[2], Murugavel Kavitha[3], Sangilidurai Karthika[1] & Periyasamy Dhevagi[1]

[1]Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Vegetable Science, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: ks75@tnau.ac.in

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Abstract

The accumulation of sludge from effluent treatment plants (ETPs) in coir industries has become a serious concern, raising critical questions about the eco-friendly management of large volumes of coir industry ETP sludge in coir-producing countries like India. This study aimed to explore a viable solution for bioprocessing the sludge and assess its potential as a soil amendment. Based on the C: N ratio and the initial characteristics of the ETP sludge, cow dung, and poultry manure were identified as potential amendments for sustainable bioconversion. The mixture was inoculated with Tamil Nadu Agricultural University (TNAU) biomineralizer, a specialized culture that aids in decomposition. The bioconversion experiment used six treatment combinations (T1 to T6) to monitor nutrient transformations. Compost from treatment T6 (50% sludge + 25% poultry manure + 25% cow dung + TNAU biomineralizer) exhibited a significant improvement in nutrient content. The efficacy of the composted sludge was further assessed through a pot culture experiment using the *Amaranthus* variety CO 6, where different proportions of the composted sludge were applied alongside recommended agricultural practices. The results revealed that treatment T8 (100% composted sludge + silica solubilizing bacteria) and the recommended package of practices combined with 100% composted sludge significantly enhanced growth parameters, including root length, shoot length, and the number of leaves, outperforming other treatments. This study highlights that the bioconversion of coir industry ETP sludge with organic amendments and TNAU biomineralizer offers a sustainable and eco-friendly solution, presenting a promising approach to advancing the circular economy.

Keywords

Amaranthus; coir ETP sludge; composting; solid waste management

Introduction

Coir products, such as coir fiber, pith, and dust, are essential to the global horticultural and agricultural sectors due to their versatility, sustainability, and flexibility. The coconut husk's excellent drainage and water-holding capacity further enhance their utility. About 80% of the world's coir fiber production, amounting to 3,50,000 metric tonnes comes from India (1). However, coir fiber production has environmental drawbacks, particularly the generation of significant wastewater that requires effective management. Coir industrial effluent contains microbes, sand, grit, stones, 28% cellulose, 29% lignin, and 8% soluble tanning-like phenolic chemicals (2). Additionally, it is rich in ammonia, calcium, magnesium, nitrates, nitrites, and exhibits high levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (3).

Common effluent treatment plants (CETPs) are often employed to manage wastewater and ensure compliance with environmental regulations. However, disposing of the sludge generated by CETPs in landfills poses severe environmental challenges (4). Developing adequate facilities for the proper processing of solid wastes is essential for aligning industrial operations with global standards (4). Unfortunately, many developing countries still rely on landfill disposal for these contaminants (5).

Landfilling CETP sludge presents critical issues, as it contains heavy metals like chromium (Cr), which can leach into soil and groundwater. This leaching can transform Cr into its highly carcinogenic hexavalent form, underscoring the urgency of adopting environmentally safe procedures for managing this toxic sludge (6).

Composting, a cost-effective bioconversion technique for sludge disposal, humifies organic material, transforming it into a fertilizer or soil amendment. Over the last few decades, extensive research has focused on modified composting systems to enhance the treatment of organic solid wastes (7). The bio-oxidative composting process stabilizes the material by mineralizing and partially humifying organic content, resulting in a final product free from phytotoxicity and pathogens (8).

In one study, a 45-day composting experiment utilized dairy waste and leaf litter in five different mixtures, with physicochemical data recorded on Days 15, 30, and 45. The mixture containing 75% leaf litter and 25% dairy sludge yielded the best results (2). Micronutrient analysis revealed reduced heavy metal mobility and bioavailability after composting. The mature compost, especially from the 25% dairy sludge and 75% leaf litter combination, demonstrated improved plant growth when tested through a pot culture experiment with spinach, as indicated by growth and biochemical parameters. Similarly, latex ETP sludge was composted with sawdust, cow dung, and coir pith over 120 days using a *Streptomyces sp*. inoculum (9). Co-composts containing cow dung exhibited higher nutrient levels, while organic matter stabilization led to near-neutral pH levels. T2 (sludge + cow dung) and T5 (sludge + cow dung + coir pith) showed ideal C: N ratios and proved effective as biofertilizers for cowpea, enhancing growth and yield, thereby demonstrating their potential in agriculture.

Effective composting requires bulking agents to prevent compaction, facilitate gas exchange, and regulate moisture levels (10). Composting industrial sludge emerged as an effective waste management strategy in sustainable agriculture and the circular economy. Adding compost to soil enhances nutrient recycling and supports microbial activity while addressing multiple waste streams simultaneously (11). Co-composting further amplifies the benefits by improving compost quality, recycling nutrients, and aligning with circular economy principles (12). However, producing high-quality compost also depends on maintaining a balance of materials during the process (13).

Research on coir industry ETP sludge highlights the importance of optimizing mixing ratios with additives such as cow dung and poultry waste. Additives like poultry manure, sugarcane filter cake, and cow dung can mitigate odor issues and produce biofertilizers that meet national standards. Poultry manure, in particular, has been shown to enhance nutrient content and accelerate compost maturity (14). Coir ETP sludge is hypothesized to yield good compost when combined with poultry waste and cow dung in an appropriate ratio. To assess quality, tests were performed for germination index for maturity (1) and phytotoxicity (2), as well as verification of the lack of starch and indicating a stable compost (3).

Materials and Methods

Coir industry ETP sludge and its initial characteristics

In this study, ETP sludge was sourced from M/s Remmy substrates India, a private coir processing industry in Coimbatore district, Tamil Nadu, India. A physico-chemical analysis of the coir ETP sludge was conducted to determine its initial characteristics. The analysis included parameters such as pH, EC, temperature, moisture content, nitrogen (N), phosphorus (P), potassium (K), organic carbon (OC), C: N ratio, lead (Pb), nickel (Ni), zinc (Zn), copper (Cu), cadmium (Cd) and Cr (15, 16). All parameters were analyzed using standard analytical methods (Table 1).

Amendments and bioconversion experiment

To optimize the C: N ratio, enhance decomposition, and improve the nutrient quality of the coir industry, ETP sludge, poultry waste, and cow dung were incorporated as amendments in various proportions, as detailed in Table 2. The treatment ratios were designed to balance the C: N ratio, drawing on insights from previous studies on the composting of industrial sludges (9, 16). Additionally, microbial culture was introduced to accelerate decomposition, producing a nutrient-rich material suitable for use as manure.

The bioconversion experiment used six treatment combinations (Table 2) following the heap composting method. Each compost heap was maintained at a minimum size of 1 m^3 and weighed approximately 450 kg. The control pile consisted solely of coir ETP sludge and was observed for 105 days. The heaps were subjected to aerobic composting, with regular watering to maintain optimal moisture levels and periodic turning to ensure uniform decomposition. Fig. 1 illustrates the experimental setup of compost beds consisting of six treatments and four replicates.

Physicochemical changes during the bioconversion process

Physicochemical changes were monitored by periodically collecting samples and analyzing them in the Department of Environmental Sciences Laboratory, Tamil Nadu

Table 1. Physico-chemical analysis methods for coir ETP sludge, poultry waste, and cow dung

Parameters	Methodology	Reference
Moisture (%)	Hot air oven method	(17)
pH	Potentiometry in soil and water suspension (1:10) ELICO LI 120)	(18)
EC (dS m^{-1})	Conductometry in soil and water suspension (1:10) (ELICO CM 180)	(18)
Total nitrogen (%)	Diacid extraction – Kjeldahl method	(19)
Total phosphorous (%)	Triacid extraction – Spectrophotometric method	(20)
Total potassium (%)	Diacid extraction – Direct aspiration in Flame photometer	(18)
Organic carbon (%)	Wet digestion method using chromic acid	(18)
Compost maturity test	Starch iodine test	(21)
Heavy metal (mg kg^{-1})	Acid digestion with aqua regia (mixture of hydrochloric acid (HCl) and nitric acid (HNO_3) with the ratio of 3:1), direct aspiration with MP-AES	(22)

Table 2. Mixing ratios of coir ETP sludge, poultry manure, and cow dung for composting

Treatments	Feedstock and combination	Ratio v/v
T1	Sludge (100%)	1:0
T2	Sludge (75%) + Poultry manure (25%)	3:1
T3	Sludge (50%) + Poultry manure (50%)	1:1
T4	Sludge (75%) + Cow dung (25%)	3:1
T5	Sludge (50%) + Cow dung (50%)	1:1
T6	Sludge (50%) + Poultry manure (25%) + Cow dung (25%)	2:1:1

Agricultural University, Coimbatore. Parameters such as pH, EC, temperature, moisture content, N, P, K, OC, C: N ratio, Pb, Ni, Zn, Cu, Cd (15), and Cr were analyzed using standard methods (Table 2).

Compost maturity assessment

Compost maturity was assessed using the Starch Iodine test and Lead sulfide test to evaluate the decomposition status of the final product.

Starch Iodine Test: A 1g compost sample was placed in a 100 mL beaker with a few drops of ethanol and 20 mL of perchloric acid. The mix was thoroughly stirred and filtered using Whatman No. 40 filter paper. A few drops of the filtrate were transferred onto a white tile, and two to three drops of iodine reagent were gradually added. Immature compost resulted in a dark-colored residue, whereas mature compost produced very little precipitation with a yellowish color (Fig. 2) (21).

Lead Sulphide Test: A 1g compost sample and a lead acetate strip were placed in a test tube. Hydrochloric acid (18%) was carefully added along the inner walls of the test tube, ensuring it did not come in contact with the lead acetate strip. The absence of black coloration on the strip indicated the presence of mature compost (21).

Quality characteristics of bioprocessed coir industry ETP sludge

The characterization and laboratory analysis of the bioprocessed sludge was conducted using standard methods, as mentioned. Structural analysis of the decomposed materials was performed using a scanning

Fig. 1. Bioconversion experiment: Compost heaps.

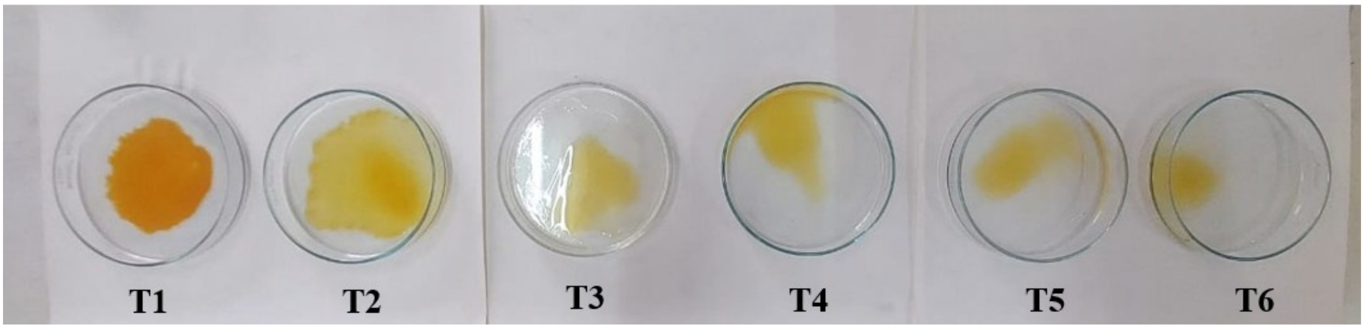


Fig. 2. Results of starch iodine test.

electron microscope (SEM, M/s FEI-Quanta 250, Czech Republic).

Bioprocessed coir industry ETP sludge application on *Amaranthus* germination and growth

The bioprocessed coir ETP sludge from the best-performing treatment was evaluated for its impact on the germination and growth of the edible leafy vegetable *Amaranthus* (Order: Caryophyllales, Family: Amaranthaceae). This was assessed through a pot culture experiment (Fig. 3) comprising eight treatment combinations (Table 3). Each pot, measuring 14 inches in height and 12 inches in diameter, was filled with 10 kg soil.

Silica solubilizing bacteria (SSB) was incorporated into the experiment at the recommended fertilizer dose at the rate of 2 kg per ha. Silica (Si) supplementation is known to have several benefits, such as an improved immune system, enhanced neurological function, and better nail and hair quality. Increasing Si uptake in crop plants sustainably improves yield, as SSB solubilizes K and silicate, reducing the dependence on artificial fertilizers (23). The SSB culture in this study was obtained from the Agricultural College and Research Institute (AC&RI), Madurai, Tamil Nadu Agricultural University.

Root architecture analysis

The root architecture of *Amaranthus* plants from the pot culture experiment was analyzed to assess the effect of bioprocessed coir industry ETP sludge application on root development. Representative plants were harvested, and the soil particles adhering to the root surface were completely removed by thoroughly washing the roots with water. After cleaning, the root system was cut into small pieces and carefully placed in a transparent tray (20 x 15 x 2 cm) filled with water to minimize root overlap. The tray was then scanned using an Epson Perfection V800 photo scanner. The scanned images were analyzed using the WinRHIZO Pro image system (Regent Instruments, Inc., Quebec City, QC, Canada) to estimate total root length, root surface area, average root diameter, and root volume, expressed in cm, cm^2, mm, and cm^3, respectively.

Fig. 3. Pot culture experiment for *Amaranthus* sp.

Statistical analysis

Statistical analyses were performed using SPSS version 16.0.0. Analysis of variance (ANOVA) was conducted for each dataset to calculate the means and standard deviations. Significant differences between the variables were determined at a 95% confidence level, and the results were reported as mean ± standard error.

Results and Discussion

Physio-chemical characteristics of coir industry ETP sludge

Coir ETP sludge, poultry wastes, and cow dung were found to be alkaline, with pH values of 8.8±0.12, 8.56±0.07, and 8.87±0.11, respectively. These pH levels are considered favorable for composting as they help reduce pathogenic microorganisms and promote the activity of beneficial composting microbes (24). Poultry waste and cow dung exhibited slightly higher electrical conductivity (EC) values (2.5 ± 0.05 dS m^{-1} each) compared to sludge (0.82 ± 0.02 dS m^{-1}), all within acceptable limits for composting processes (25).

Poultry wastes exhibited the higher OC content (30.29±8.57%), closely followed by cow dung (28.37±8.02%), both significantly higher than that of sludge (15.01±4.15%). This higher OC content facilitates the composting process by serving as a substrate for the growth and activity of decomposer microorganisms (26). Cow dung recorded the highest total N content, followed by poultry waste, due to their higher levels of proteins and amino acids compared to sludge (27) (Table S1). Total N content in sludge was recorded at 0.51±0.01%, resulting in a C: N ratio of 36.5±0.57, suggesting the need for N supplementation. Additionally, the sludge contains 0.32±0.01% total P and 0.16±0.01% total K. However, the heavy metal concentrations in the sludge were within the permissible limits.

Nitrogen-rich feedstock is essential to achieve the ideal C: N ratio required for efficient composting. Poultry waste, with its higher P and K levels than sludge, can significantly enhance soil fertility and promote plant growth when the compost is applied to agricultural fields (28, 29).

Changes in the physio-chemical properties

Temperature and moisture dynamics in the composting process: The study monitored temperature fluctuations in

Table 3. *Amaranthus* experiment: Treatment details under pot culture

Treatments	Treatment details
T1	Recommended package of practices (RPP)
T2	RPP + 50% CS
T3	RPP + 75% CS
T4	RPP + 100% CS
T5	RPP + 50% CS + SSB
T6	RPP + 75% CS + SSB
T7	RPP + 100% CS + SSB
T8	100% CS + SSB

compost piles over 105 days across six treatments (T1-T6) (Fig. 4). Temperature measurements were recorded every 15 days using digital temperature and moisture meters. To ensure optimal moisture levels for decomposition, the compost piles were turned and watered at the same 15-day intervals.

At the start of the experiment, temperatures ranged between 25.6±0.15°C to 27.7±0.28°C. By the 30th day, all treatments exhibited increased temperature, with T6 reaching the highest (35.8±0.18°C), followed by T3 (34.3±0.4°C). On the 60th day, T6 maintained the highest temperature (33.4±0.05°C), likely due to the addition of poultry manure, which acts as an activator and accelerates degradation compared to other manures (30, 31).

By the 90th and 105th days, temperatures declined across all treatments, however, T6 consistently demonstrated higher values (30.5±0.09°C and 26.4±0.42°C, respectively). Regular mechanical mixing and watering improved temperature distribution within the compost piles (32). Bulking materials like cow dung and poultry manure enhanced aeration, supporting microbial respiration (10) and promoting exothermic microbial activity, elevating temperatures (26). Nevertheless, as smaller composite piles tend to lose heat more quickly, the temperatures in all treatments remained below 40°C throughout the study (33).

Initially, T1 exhibited the highest moisture content (55.5±0.5%), while T3 recorded the lowest (47±0.71%). The initial moisture content across treatments fell within the optimal 40-65% (34). The observed rise in temperature during the early composting stage was likely influenced by

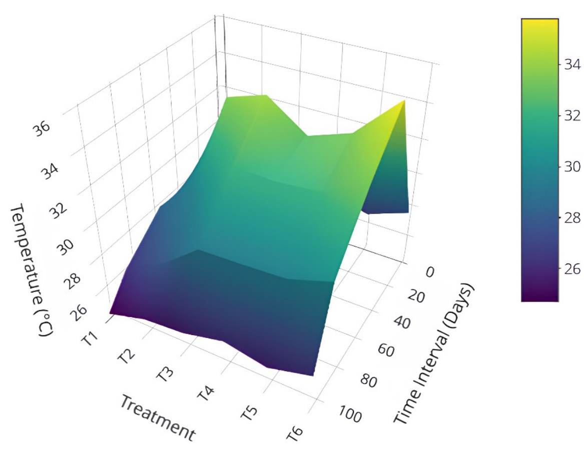


Fig. 4. Changes in temperature during composting.

the gradual increase in moisture content due to the periodic addition of water (35).

By the 30th day, moisture content decreased across all treatments, with T4 (43.9±0.38%) and T3 (44.8±0.11%) showing the lowest levels. At 60 days, T4 maintained the lowest moisture content (40.7±0.03%). This decline in moisture can be attributed to the high temperatures observed during this period, which likely increased water vaporization (31).

By the 90th and 105th days, a general increase in moisture was observed across all treatments, with T1 showing the highest moisture (56.8±0.93%) at the end of the study. Rainfall fluctuations influenced variation in moisture content throughout the composting process in temperature. Fig. S1 presents the changes in moisture levels over the composting period.

pH: The pH levels of the compost samples throughout the experiment ranged from 7.87±0.1 to 8.7±0.13, with a consistent decline observed during the composting process, as presented in Table S2. For instance, the pH of T3 decreased from an initial 8.4±0.13 to 7.92±0.03, while T6 showed a reduction from 8.79±0.14 to 7.87±0.1 by the 105th day (Fig. S2). This decline in pH is attributed to the biological activity of aerobic decomposition, which produces hydrogen ions, leading to increased acidity (36).

At the beginning of the composting process, the pH shifts towards acidity due to the incomplete oxidation of organic acids in the composting mixture (37). By the 105th day, the final pH values of the compost piles ranged from 7.87 ± 0.1 to 8.7 ± 0.13, all falling within the optimal pH range of 5.5 to 9.0 (36). These findings were statistically significant at $p < 0.05$.

Electrical conductivity (EC): Variations in soluble salt concentrations across treatments were evident at the start of the composting process, as reflected by the EC values, which ranged from 1.77 dS m^{-1} in T4 to 2.62 dS m^{-1} in T6 (Table S2). These differences can be attributed to the varying initial compositions of the composting materials, microbial activity, and the incorporation of different amendments (38, 39). Initially, T6 recorded the highest EC (2.62 ± 0.03 dS m^{-1}), followed by T2 (2.47 ± 0.04 dS m^{-1}). By the 30th day, all treatments exhibited a decrease in EC levels (Fig. S3). This declining trend continued to the 105th day, with T2 (1.98 ± 0.01 dS m^{-1}) and T6 (1.91 ± 0.03 dS m^{-1}) showing significant reductions. The decline in EC is influenced by composting-related processes such as the precipitation of soluble salts, ammonia volatilization, and the leaching of ions during decomposition (39). This final EC value, ranging between 0 and 2 dS m^{-1}, falls within the optimal compost quality range (40).

Gains and losses of organic carbon, nitrogen, and C: N ratio: T1 demonstrated a decrease in OC from 18.71±0.27% to 14.5±0.12%, while T2 showed a more pronounced reduction from 17.4±0.19% to 12.5±0.02%, making it one of the more effective treatments. A consistent decrease in OC was observed across all treatments over time (Table S2). Similarly, T5 significantly declined, from 18.3 ± 0.28% to 13 ± 0.11%. T6, which initially had the highest OC content (19.9 ± 0.18%), reduced to 15.7 ± 0.04%. Carbon losses during composting are most significant during the early mesophilic and thermophilic stages, as microbial activity peaks and carbon-rich substrates are abundant during the initial composting phase (41). The high initial OC content in compost indicates elevated microbial activity compared to lower N compounds during the early stages (41). Fig. S4 shows the changes in OC% at various time intervals during composting. Notably, T5 and T6 displayed a steady decline in OC content throughout the process (42).

The N content varied across all treatments, with the lowest initial values recorded for T1 (0.43 ± 0.01%) and the highest for T6 (0.88 ± 0.01%) (Table S2). Over time, all treatments increased N content, indicating efficient decomposition and nutrient conversion during composting (Fig. S5). The increase in total N content is attributed to the loss of dry mass caused by microbial activity (31) which releases carbon dioxide and evaporates water until the compost reaches maturity (43). In the final week of composting, the highest N levels were observed in T6 (1.3 ± 0.01%), while T1 had the lowest values (0.69 ± 0.01%). This increase in N content is primarily due to the concentration effect resulting from the substantial breakdown of organic matter and the contribution of N-fixing bacteria, as highlighted in previous studies (44). The order of N availability among the composts was T6 > T3 > T5 > T2 > T4 > T1. This pattern suggests that enhanced aeration and effective temperature control promoted greater microbial activity during composting (10).

Initially, T1 exhibited the highest C: N ratio at 43.5±0.58, which decreased to 21.02±0.34 by the end of the composting period. Similarly, T6 showed a reduction in its C: N ratio from 22.62±0.24 to 12.08±0.05 (Fig. 5). These reductions indicate that certain treatments are approaching a stable phase as the material becomes increasingly humified and enriched with nutrients (45). The composting materials' initial C: N ratios showed that T1 had a higher ratio, signifying a greater carbon content relative to N. While within permissible limits, the final C: N ratios suggest that the composting process might be relatively slow for some treatments (46). Achieving an appropriate C: N ratio is essential for producing nutrient-rich compost free from phytotoxic compounds. A C: N ratio between 10-20:1 is ideal for mature compost (28).

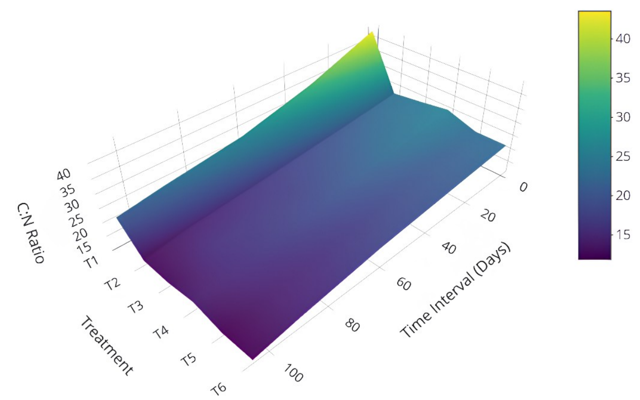


Fig. 5. Changes in C: N ratio across different intervals.

Phosphorus: The P patterns across the treatments during composting were distinct and evolved, as shown in Table S2. At the start of the process, the lowest P value was observed in T1 (0.26 ± 0%), while T3 had a higher initial value of 0.89 ± 0.01%. Throughout the composting process, all treatments exhibited an increase in P levels (Fig. 6). By the 105th day, T1 reached 0.42 ± 0.01%, while T3 peaked at 1.25 ± 0.02%. T6, which started with 0.83 ± 0.01%, exhibited the highest P levels, rising to 1.29 ± 0.01%.

During composting, active microorganisms improve

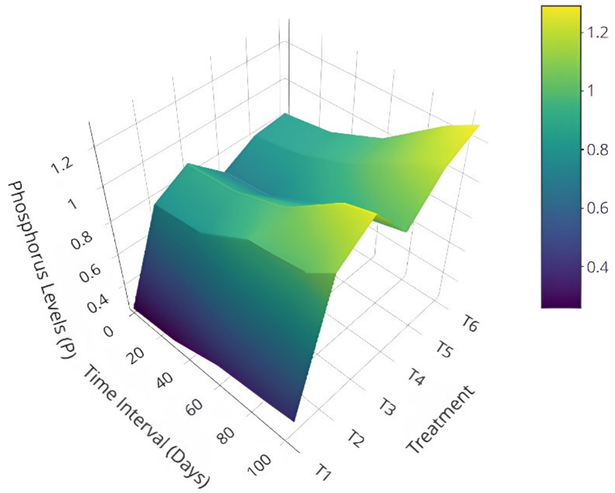


Fig. 6. Changes in phosphorus % across different time intervals during composting.

the quality and availability of organic matter. The accelerated rate of carbon losses during the decomposition of organic compounds may have contributed to the concentration effect, which likely led to increased P content (16).

Potassium: Throughout the composting period, T6 showed maximum K content, followed by T3, T5, T4, and T2, with T1 showing the minimum. Initially, the lowest amount of K at 0.19±0% was found in T1, and the highest K concentration at 0.77 ±0.01% was found in T6, as shown in Table S2. The specific treatment factors and the maturation process of the composting materials significantly influenced the variations in K availability. Different compost materials, such as poultry manure with higher absorbency potential and small pore spaces, contribute to higher K values in compost, making it more beneficial for improving soil health—especially when combined rather than used separately (47, 48). K values in T6 consistently increased throughout composting, starting from higher initial levels and reaching 1.14 ± 0.01%, indicating effective nutrient accumulation and stability. Fig. 7 illustrates the changes in K percentage across various time intervals during composting. Several factors, including microbial activity, the characteristics of organic substrates, and pH, influence K availability during the composting process (49).

Micronutrients: During the composting period, variation in micronutrient content was observed across all treatments. T6 showed the highest concentration of micronutrients on

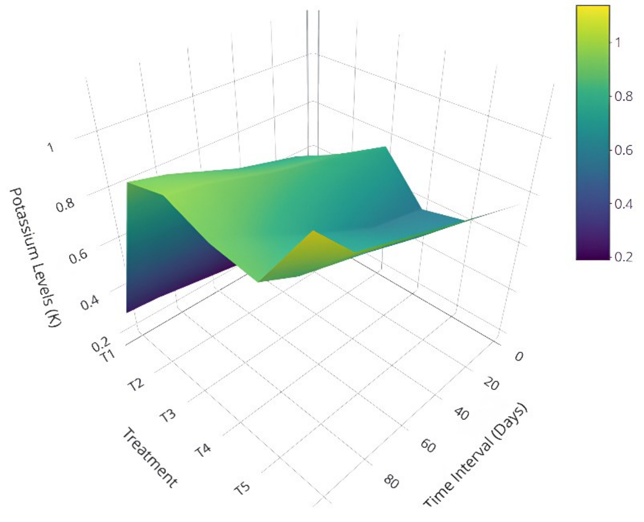


Fig. 7. Changes in potassium % across different time intervals during composting.

Day 105, with Cu at 0.38 ± 0.01 ppm, Zn at 1.7 ± 0.03 ppm, and Fe at 52.1 ± 0.86 ppm. It was noted that organic amendments promote the accumulation of metals in compost (50).

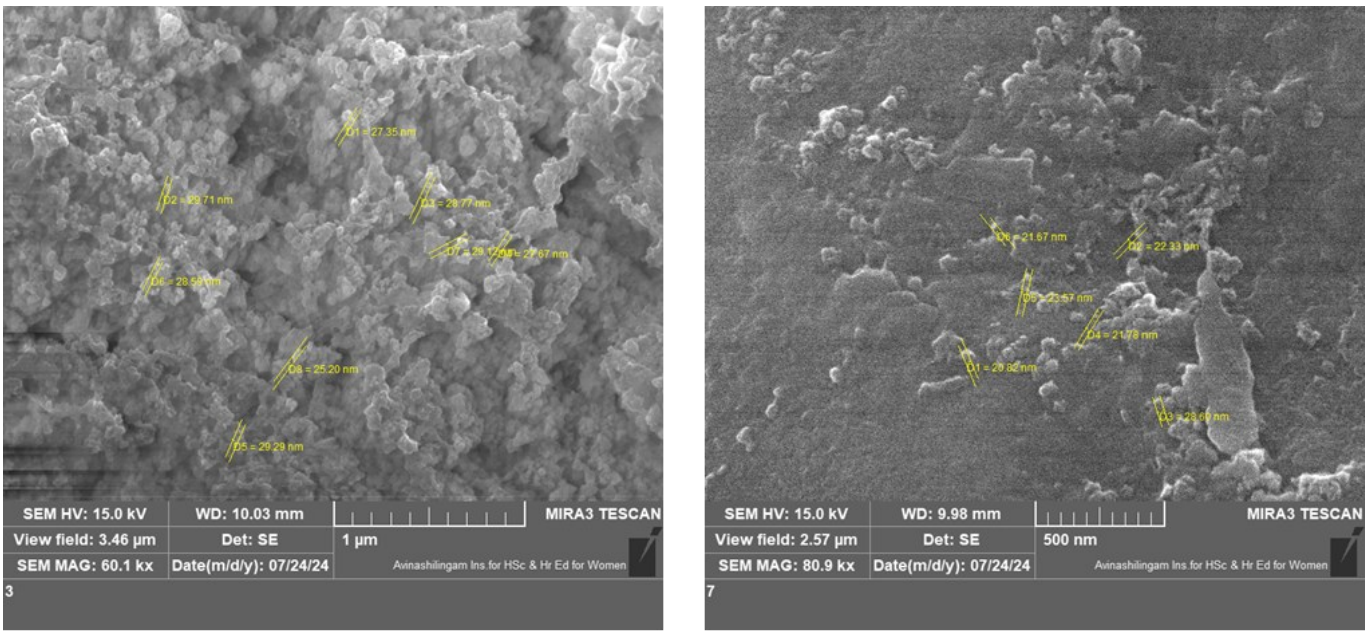
Scanning electron microscope analysis: Fig. 8 illustrates the significant changes in coir ETP sludge as it undergoes degradation. As the composting process advances, Fig. 8 (A) shows untreated sludge samples, while Fig. 8 (B) shows the composted sludge sample. These images highlight the sludge's progressive degradation, with a noticeable reduction in particle size compared to the material present before composting (51).

Influence of various doses of ETP sludge biocompost on germination and growth of Amaranthus sp.

Germination: The study assessed the impact of various treatments on seedling germination, growth, and vigor, revealing significant differences across the treatments, as presented in Table S3. Notably, T8 exhibited the highest germination rate (95.3±1.1%), closely followed by T4 (94.3±1.69%), suggesting optimal conditions for seed germination due to enhanced nutrient availability and soil structure. T4 also demonstrated superior shoot length (6.6±0.08 cm) and root length (2.7±0.01 cm), followed by T8, which had a shoot length of 5.7±0.11 cm and a root length of 2.4±0.04 cm (33). The number of leaves was highest in T8 (5.67±0.28), indicating enhanced photosynthetic capacity and plant vigor (33). In conclusion, T4 and T8 emerged as the most effective treatments, with significant improvements in germination, growth, and vigor, underscoring their potential for sustainable agriculture and optimal plant development (Fig. S6). Applying composted sludge fertilizer significantly improved crop growth parameters and increased yield by 124.2%, demonstrating its efficiency in promoting plant growth (52).

Growth of *Amaranthus sp.*: Table S4 presents the effect of various compost treatments on *Amaranthus* growth, evaluated in terms of shoot length and the number of leaves at intervals of 15, 25, and 35 days. The results indicated that treatment T4 resulted in the highest shoot length, with an average of 6.6±0.08 cm on the 15^{th} day, 15.6±0.33 cm on the 25^{th} day, and 32.7±0.62 cm on the 35^{th} day. Treatment T8 showed the most significant results regarding leaf production, with an average of 5±0.04 leaves on the 15^{th} day, 22.6±0.41 leaves on the 25^{th} day, and 30.2±0.31 leaves on the 35^{th} day. These findings suggest that combining 100% compost and SSB (T8) significantly enhanced leaf production, while treatment T4 promoted greater shoot elongation (38). The plants showed an improvement in growth parameters and regulated the concentration of essential and minor nutrients to optimal levels, thereby improving the overall development and growth.

Root architecture analysis: The analysis of root parameters for *Amaranthus* under different compost treatments revealed significant variations (Table S5). Among the treatments, T8 demonstrated the most pronounced root



A **B**

Fig. 8. Scanning electron micrographs of (A) untreated sludge samples (B) composted sludge samples .

development, with the longer root length (245.67 cm), followed by T4 (150.17 cm) and T6 (104.50 cm). T5 exhibited the highest projected area (22.86 cm^2) and surface area (71.83 cm^2), indicating substantial root spread and volume, along with the highest number of tips (1724), forks (1906), and crossings (235). In contrast, T1 displayed the shortest root length (23.60 cm). Overall, T8 and T4 were the top performers regarding root length, while T5 excelled in root structure complexity. Fig. 9 shows the visual inspection of the root architecture of *Amaranthus sp.*

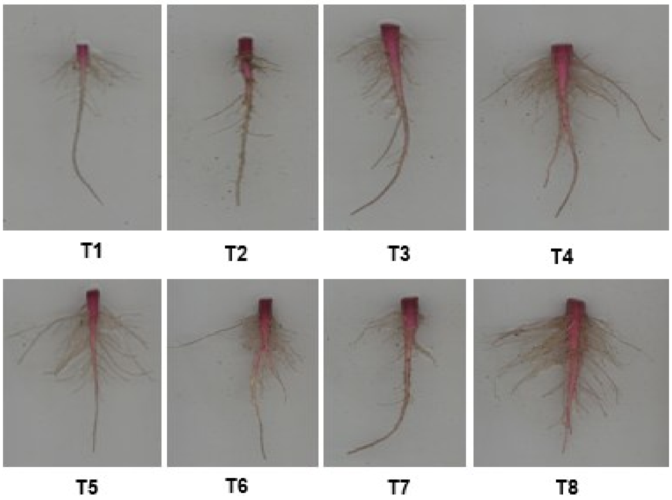


Fig. 9. Root architecture of *Amaranthus sp.*

Conclusion

The present study revealed that coir industry ETP sludge can be bioprocessed into a stable, decomposed product by using cow dung and poultry manure as amendments, along with TNAU biomineralizer as the decomposing culture. Based on the observations, T6 (sludge (50%) + poultry manure (25%) + cow dung (25%)) with TNAU biomineralizer at 2 kg/ton performed well with significant improvements in N, P, and K content, as well as a reduction in pH and EC. These changes indicate better compost maturity and nutrient content than the other treatments. The study on the application of bio compost obtained from the coir industry ETP sludge to *Amaranthus sp.* showed that the bioprocessed sludge is highly suitable for crop production, as evidenced by significant improvements in soil quality and plant growth. The bioprocessing of coir industry ETP sludge with amendments and its positive effects on *Amaranthus sp.*, provides a sustainable solution to sludge disposal while supporting a circular economy within coir industry effluent treatment plants. The future of composting industrial sludges holds great potential for advancing a circular economy by turning waste into valuable resources. As industries generate large amounts of sludge, traditionally considered waste, composting offers a sustainable solution to repurpose this material into organic fertilizers or soil conditioners. Advances in biotechnological treatments and microbial inoculants can improve the efficiency of sludge degradation, reducing potential contaminants and enhancing nutrient content.

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Authors' contributions

PRD carried out the composting trial and drafted the manuscript. KS conceived the study and supervised the research process. MM contributed to the conceptualization and planning of the study. KSB reviewed and revised the manuscript for intellectual content. MK was responsible for acquiring the necessary resources. SK reviewed and revised the manuscript for intellectual content. PD secured funding for the project and provided resources for the study.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used CHATGPT 4.0 to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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