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Efficient plant leaf biomass management through ECO-leaf composter using structured decision-making techniquefor optimal dry leaf composting selection

ABSTRACT

Sustainable management of leaf biomass, including leaves, petioles, twigs, and other aboveground plant materials, has become a significant challenge in both residential and municipal settings. The Eco-leaf composter was developed as a sustainable solution, and its efficiency was evaluated through five trials (T1, T2, T3, T4, and T5) for a period of 30 days, each using different forms of plant leaf biomass.T1 used grinded form of plant leaf biomass with organic inoculum, andT2 used grinded plant leaf biomass withoutan optimum quantity of handmade organic inoculum using valuable ingredients, In T3unshredded form of plant leaf biomass with organic inoculum was used, while in T4shredded form of plant leaf biomass with organic inoculum and inT5 shredded form of plant leaf biomass was experimented without the use of organic inoculum. Compostingtemperatures were maintained between 50°C and 60°C, with moisture content kept at approximately 65% throughout the process. The Analytical Hierarchy Process (AHP) was employed to identify the best-performing trials. Among all trials, T1demonstrated the highest composting efficiency, with a pH range of 7.6 to 8.6 (indicating active composting), a reduction in total organic carbon from 42% to 36.5%, an increase in total nitrogen from 0.7% to 1.3%, and a decrease in the C:N ratio from 57.8 to 28.3 over 30 days. Also, cellulose content decreased from 42.9% to 3.3%, hemicellulose from 9.8% to 0.5%, and lignin from 13% to 0.3%. Compared with T3, which was made of unmilled dry leaves, this leads to a slower rate of degradation was likely due its large leaf material size. In conclusion, we need to keep in mind how composting parameters should be set to deal with waste from gardens efficiently.This approach offers an alternative to traditional disposal methods by providing a rapid, compact,insitu,environment friendly and efficient approach to the problem.

Keywords: *Eco-leaf; thermophilic temperature;sustainability; circular economy; germination;dry leaves.*

1. INTRODUCTION

Rapid urbanization has seen a large increase in garden waste, ranging from dried leaves and cut stalks to twigs, grass and flowers. This wave currently presents great difficulty for local government departments that are trying to handle or dispose of refuse effectively. In some countries, the fermentable matter in garbage produced by the city typically accounts for about 60 % of all waste[1]. Depending upon source and collection method, garden waste makes up between 12–15 per cent of municipal solid waste.

Community parks, gardens and recreational centers in cities are at the top of this list. Garden waste is a type of compost often with a wide variety, great space needed for storage (about 50–75 kg/m³)[2], higher weight to volume ratio than other organic wastes such as vegetable peelings and food scraps. This low density and large spatial footprint make collection, transportation and disposal difficult for local authorities[3]. The main sources of garden waste are deciduous trees and conifers (evergreens). Deciduous trees dump leaves all season long but especially in autumn. Coniferous trees are more gradual about dropping their leaves and do it off and on throughout the year. This natural process of leaf shedding, termed abscission, is an adaptive measure taken by plants to save resources in response to environmental changes. Deciduous trees shed large amounts of

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leaves seasonally, while coniferous trees shed a continuous supply of needle shaped leaves. Abscission makes an important contribution to the pile of garden waste but its essence is that natural processes cannot be stopped, and so effective waste management is needed. The traditional methods of disposal, such as open dumping, burning and landfilling, are inefficient and harmful to the environment. Garden waste contains high levels of lignin, cellulose and hemicellulose compounds which rot slowly and need long periods to decompose naturally. These practices occupy large areas and produce negative effects on the environment, including emission of greenhouse gases, degradation of the soil, global warming and air pollution.

This highlights the need to provide sustainable waste management solutions, such as composting and mulching. Composting is a particularly good technique to turn garden waste into soil. Useful soil amendments which improve the soil structure and nutritive value without harming the environment. And then there's the eminent technology known as "in-vessel composting" which takes garden waste for treatment under strictly controlled conditions, hastening the breakdown both in complex organic compounds and odors, also taking environmental risks into consideration [4]. The main elements necessary for successful composting are air, water, and temperature. The composting process is divided into three increasingly warm stages: the mesophilic stage, followed by the thermophilic stage and finally completion of compost maturation each with its own particular characteristic set of micro-organisms together temperatures requirement essential to organics decomposition. According to [5], it is necessary to have a range from 50°C to 65°C to effectively break down lignocellulosic materials. Our research was able to meet these needs by keeping the reactor under thermophilic conditions throughout. Circulation of air is essential in order to activate microbial activity, keep the temperature down and bring about a stable condition in the pile. Otherwise, the microorganisms will create odors simply working because they are doing so under conditions that create them. This study had an in-vessel reactor modified with an electricity powered pump aeration system. A constant humidity level of about (65-70)% was maintained throughout all five trials, in order to promote efficient microbial action, heat production within the compost pile and avoid disadvantages posed by anaerobic conditions.

The establishment of dry leaves dedicated bioreactor offers a breakthrough for trash disposal that addresses persistent challenges in how traditional methods cause both economic waste and ecological damage.This advanced compost technology turns dry leaves into valuable organic fertilizers, thereby underscoring green solutions.In-vessel systems have a distinct advantage over regular compost using controlled conditions (temperature, aeration, moisture) in cylindrical chambers that decompose low moisture organic refuse such as dry leaves.Studies show that to obtain high quality compost and retain nutrients, biomass mixed into other organic materials will improve the end product. Elsewhere, mixing mature compost with fresh green waste activates decomposer microbes hastening the decomposition process dramatically [6] Other studies highlight the role of bulking agents which promote aeration,porosity, and assist microbial activity while maintaining moisture levels in compost for effective [7]. The mixing of plant biomass with materials such as cattle manure also enhances substrate microbial processes and restores moisture levels to the compost fundamental [8]. In-vessel composting of the high lignin content and slow decomposition material dry leaves also requires further in-depth study.

To establish a hierarchy of criteria and break down complex judgments, the Analytic Method for Making Decisions AHP is intended. AHP is widely applied throughout the project management field for decision analysis, multi-criterion assessment, and project development work. It provides systematic procedures to quantify subjective opinions. It is particularly useful when comparing alternatives in terms of their weighting across different criteria, seeing as it assigns weightings values to each criterion. AHPs have a wide range of applications in such fields as environmental management, project selection, and process planning. In this way, an AHP was employed as a tool to set composting trials into a manure pile and considered carefully with individual physico-chemical parameters. These indicators are vital because they directly determine the quality of compost which is what we all aim for in our trials. Through the use of AHP, the study found the most efficient and sustainable way to compost dry leaves. This maximizes the conditions under which bio-degradation can take place, while promoting recycling cost-benefits ecology garbage disposal scheme practice. The method makes decision making more accurate and provides a model for further research in composting and waste management practices.

More research on in-vessel composting of organic waste has already been conducted than any other single topic, but few studies take up only plant leaf as its absolute focus.This study aims to remedy this situation by making use of Analytical Hierarchy Process (AHP) as a decision making tool to find out just what is the best way for plant leaf biomass to be disposed off easily and eco-friendly by in-vessel composting technology. Geared at discerning optimum composting conditions for dried leaves, it takes into consideration that temperature, water content, types of garden waste and enhancers that help decompose them are all important variables.This method of mechanism managements for plant leaf biomass is a fresh approach. It effectively achieves better environmental outcomes.

2. MATERIALS AND METHODS

The Experiment was carried out at Sharda University, Uttar Pradesh, India, with a longitude of 77.483761 degrees and a latitude of 28.471956 degrees. The basic material was dry leaves, picked up from the campus and from many dumping spots around Greater Noida. In this way, the leaves were manually removed and chosen byclipping off contaminants extrinsic to the outerlayer, such as plastic, paper,or, if it's not permitted, they snip it out so there is an absolutely clean organic substrate left for later analysis. Because every plant produces its own characteristic looking kind of leaf, the arrangement of leaves was very different at each plant growing place. For the best compost, leaves should be placed through a pulverizing machine, which is located atSharda University campus. They grind the leaves down into pieces 2-4 cm long and a fine powder, ideal for use as compost. These preparations support the findings of previous investigators [9] that the importance of particle size in composting improvesaeration and shortens the time needed to accomplish rapid decomposition.

2.1. Eco-leaf Composter

A rectangular eco-leaf composter, measuring 1.6 meter x 1.6 meter outside, was constructed at university campus to facilitate research in temperature controlled environments. To conduct the study, a cylindrical stainless steel container with a diameter of 0.6 meters and a height of 1 meter, possessing a volume of 200liters, was utilized to house the composition of the experiment within the in-vessel reactor's shielded interior. The container was equipped with a heating rod, to heat the water provided in it so that the temperature of composting material gets increased.The equipment was outfitted with a digital display temperature control meter for reflecting the temperature of composting material,a Miniature Circuit Breaker (MCB) to mitigate short-circuiting issues,an electric knob to provide rotation to the cylindrical container, an electric knob to incorporateaeration system. Aeration pumps are integrated into the system to facilitate efficient externalaeration. The aeration pump operates for 20 minutes at one hour intervals, with a fixed rate of aeration of 0.05 m^3/min, as per the experiment conducted by [10]. To aid this composter with renewable and eco-friendly benefits the device is attached to a solar panel containing a photovoltaic cell connected to a battery for power storage. The device is fabricated as a four-legged structure equipped with wheels for stability and portability.The cross-sectional view of the device is shown in the figure 1. The goal of the composter's construction and operation is to maximize the amount of dry leaves that are composted. Manually prepared organic inoculum and tap water was added in the experimental setup to maintain the moisture level at 65%, based on moisture measurements taken every five days on the sampling days. The duration of composting for all trials was 30 days.Table 1 shows the amount of water or inoculum used in each trial.

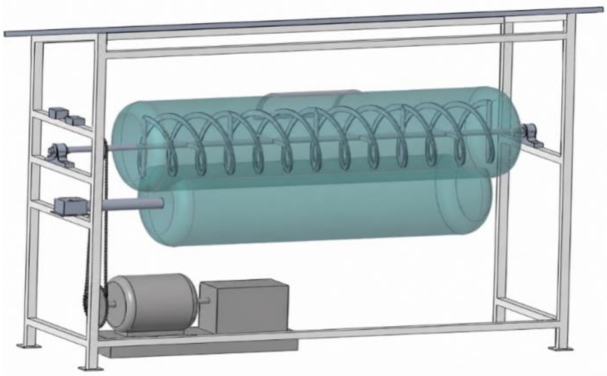

Figure 1: Cross-sectional view of ecoleaf composter

Table 1. The different combinations of dry leaves and water/ inoculum for each trial

S. No	Waste Material Type	Weight (kg)	Quantity of organic Inoculum (liters)	Quantity of Water (liters)
T1	Grinded form of Garden waste	5 kg	14 liters	Nil
T2	Grinded form of Garden waste	5 kg	Nil	18 liters
T3	Unshred form of Garden waste	2 kg	16liters	Nil
T4	Shredded form of Garden waste	3 kg	15liters	Nil
T5	Shredded form of Garden waste	3 kg	Nil	20 liters

2.2 Organic Inoculum

At Sharda university environmental engineering laboratory an organic inoculum was made by mixing distilled water (25 liters), cow dung(1 kg), jaggery(750 grams), chickpea flour(50 grams), and organic compost powder(125 grams) in a drum. It was left undisturbed for 7 days to ferment. After this period, an additional 25 liters of distilled water was added to the drum increasing the activity of the microbial product for use in the experiments. Although all biomass samples were contained in a similar volume inside the in-vessel reactor, the densities and porosities of the samples caused considerable differences in the mass of the biomass samples (Table 2).

While the addition of organic inoculum did not significantly alter certain individual parameters, it acted as a catalytic agent by enhancing microbial activity and improving composting efficiency. It also served as a sustainable substitute for tap water in maintaining optimal moisture content . In trials such as T2 and T5, where only tap water was used, composting was achieved but with slower degradation rates and lower maturity indicators. Additionally, the temperature controlled environment played a critical role by sustaining thermophilic conditions (50℃–65°C), which accelerated organic matter breakdown, promoted pathogen reduction, and ensured uniform compost maturation across all treatments.

Table 2. Porosity and density of different garden waste forms

Sr.no	Forms of Garden Waste	Density (Kg/l)	Porosity
1	Unshredded form	0.1	70
2	Shredded form	0.3	45
3	Grinded form	0.9	40

2.3. Parameter Analysing Method

Each set of ten conditions was examined in three independent tests and the mean was reported. Each of three different positions in a compost box had 500g test material taken from the middle, top and bottom layers respectively. Finally, after a uniform period of time drying (from 24 to 72 h) at 80± 2°C in an oven all samples were then compressed into one detail file. After that they were subsequently dried would be grinded and screened with a 0.25 mm sieve for subsequent physicochemical examination. An electronic thermometer was used to measure temperature, after each sampling. Acidity (pH), electrical conductivity (EC) and moisture content were tested in accordance with appropriate standards from classic literature on each factor: (BIS No. 10158; apparent specific gravity at saturated surface dry condition). Some testing on the other hand, such as volatile solids, total carbon content,nitrogenwas done [11] to determine physical-chemical properties which are essential for evaluating turn quality compost [12].

Atomic absorption flame photometer was used to test compost for the contents of Na, K and Ca. The samples were examined by Atomic Absorption Spectroscopy (AAS) for further element analysis, each ICP/AES specific wavelength with argon gas was employed to analyse and determine the contents of Mg, Cu, Mn, Fe and Zn. Although not directly comparable, have conceived methods based on the sequential determination of NDF (neutral detergent fiber), ADF (acid detergent fiber) and ADL (acid detergent lignin) in the papers describing various types. This analysis is to distinguish structural carbohydrates and lignin from other materials in lignocellulosic biomass. As by different means the organic inoculum may perhaps introduce especially if it is of sugar content or contains lignocellulosic remains, parallel samples without the addition of biomass for the same treatment were taken on at the same time. Adding the cellulose, hemicellulose, and lignin provided only by the biomass under study back from the measurements on the composite samples of compost thus excluded this bias [13]. This allowed the breakdown of the primary feedstock to be represented in compositional analysis rather than any disturbances due to inoculum.Germination studies using rice seeds were used to examine the phytotoxicity and maturity of the final product. The Germination Index (GI) was derived from this by normalizing it against analyses in vaccinations and mortality statistics (Table 1)

Several parameters were considered of great importance to be examined continually in various stages during the processof 30 days while composting, at interval of five days. These parameters indeed were temperature, moisture content, pH and some nutrients important like Phosphorus (P), Nitrogen (N) and Potassium (K)[14]. This would allow for us to have a full picture of the temporal profile related to biochemical transitions and the degradation process in terms of efficiency as discussed in (Table S 2). The entire experimental process is depicted in Figure 2.

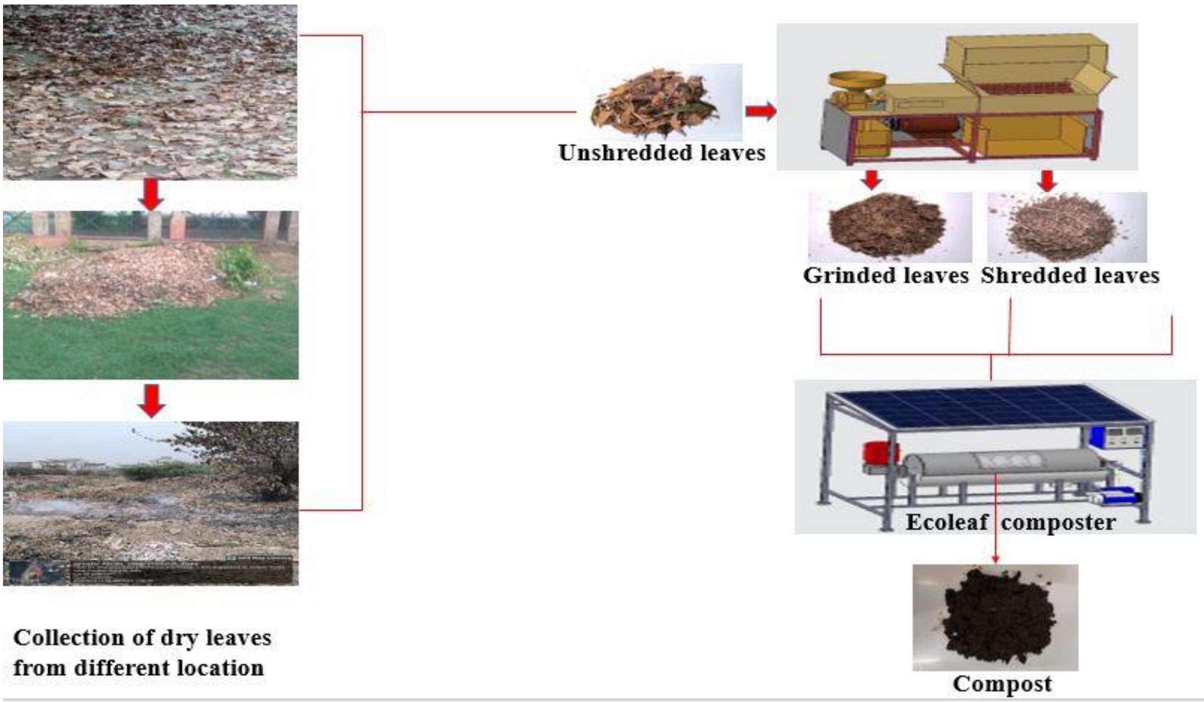

Figure 2. Pictorial representation of process flow of the study

The variation in all biological and physico-chemical parameters was assessed using a one-way Analysis of Variance (ANOVA), with a significance level set at $p < 0.05$. SPSS 13.0 software were utilized for computation of variance. As shown in table S1.

2.4. Analytical Hierarchy Process

However, AHP is a combination of quantitative and qualitative data. Since qualitative values have no scale, they are resolved into absolute numbers by applying proper scales. Normalization is applied to make these attributes dimensionless because comparing them directly is difficult, as the attributes involved generally have different units. The geometric means method most commonly used method in AHP, which is simple and easy to calculate eigenvalues as well as minimizes judgemental inconsistencies. Attribute intensities are determined from expert opinion surveys. AHP has proved to have effective wide application in various domains, including education [15], health care [16], environmental decision making [17], and energy policy[18].

3. RESULTS AND DISCUSSION

3.1. pH, Moisture, Temperature, Electrical conductivity, Phosphorus, Potassium, Total volatile solid,Total organic carbon (TOC)

The pH level is a key component of compost maturity, as it reflects the organic matter decomposition rate& influences the activity of microbes within the composting environment. The pH undergoes considerable alteration during the composting process [8], first decreasing due to the influence of organic acids that facilitate the decomposition of complex substrates. The baseline pH value for all trials ranged from 7.3 to 8.6, as each trial utilized identical plant leaf biomass. It eventually raised due to the influence of thermophilic temperatures, enough hydration, and aeration. Among all trials T1, T2, T3, T4, and T5, the pH of the finished compost reached an the range of 8.2 to 8.6,which is alkaline in nature (Fig. 3(B)). In the thermophilic phase, the pH rises due to increased ammonia volatilization and electrolyte concentrations. As compost matures, pH levels stabilize, supporting diverse stabilization process compilation and microbial communities. Regular monitoring of pH levels throughout the process is essential for maintaining optimal conditions for microbial activity.

The moisture content plays a vital role in efficient composting by influencing substrate decomposition and microbial activity[19]. Monitoring moisture levels in this study was essential to evaluate the composting process's efficiency and ensure a suitable for microbial growth. The moisture percentage across every trial was standardized in range of (65-75) % (Fig. 3(C)). In trials T1, T3, and T4inoculum were used, whereas in experiments T2 & T5 utilized tap water for moisture maintenance .T1needed the minimal inoculum of 14 liters, whereas T3 required the maximal addition of 16 liters to sustain the proper moisture content.

Temperature is the major factors affecting the composting process as it's regulate the degradation rate and the early process of thermophilic phase. Higher temperatures improve the degradation of lignocellulosic components, a prerequisite for effective composting, notably in in-vessel composting systems. During all experiments, the thermophilic phase was initiated at the beginning of the experiment and temperatures were held constant at 55°C (Fig. 3(D)) until the 30th day of composting. The temperature ranges were between 55°C -58°C for trials T1, T2, T4, and T5 while a more extensive temperature range of 50°C - 58°C occurred in trial T3 fine samples enhanced the progression of temperature and indirectly encouraged mesophilic microorganisms. Therefore, pile temperature is a reflection of degree of composting and microbial activity [20].

Electrical conductivity (EC) is a crucial parameter in agriculture and horticulture, as it indicates the concentration of salts in compost and the extent of degradation. Electrical conductivity (EC) indicates the concentration of ions, including phosphate, potassium,ammonium, and nitrate, produced from decaying organic matter in a solution [21]. A reduction in electrical conductivity (EC) signifies compost stabilization and maturation, as evidenced by all trials (T1, T2, T3, T4, and T5), which exhibit a declining trend in values (Fig.3 (A)). In the initial measurements, T1 exhibited the lowest value of 1.16 mS/cm, while T2, T3, T4 and T5 displayed nearly identical initial electrical conductivity values. A significant reduction in values across all trials was observed post 10 days, coinciding with activity of microbes during the thermophilic phase, which influences saline concentration. On the final day, T1 recorded the lowest value of 0.549 mS/cm, attributed to the decreased volume facilitating microbial activity in composting. Increased electrical conductivity (EC) levels might hinder plant growth and obstruct seed germination. Electrical conductivity (EC) indicates soluble salts concentration, including ammonium, potassium, nitrate, and phosphate released by decaying organic matter in a solution [7].

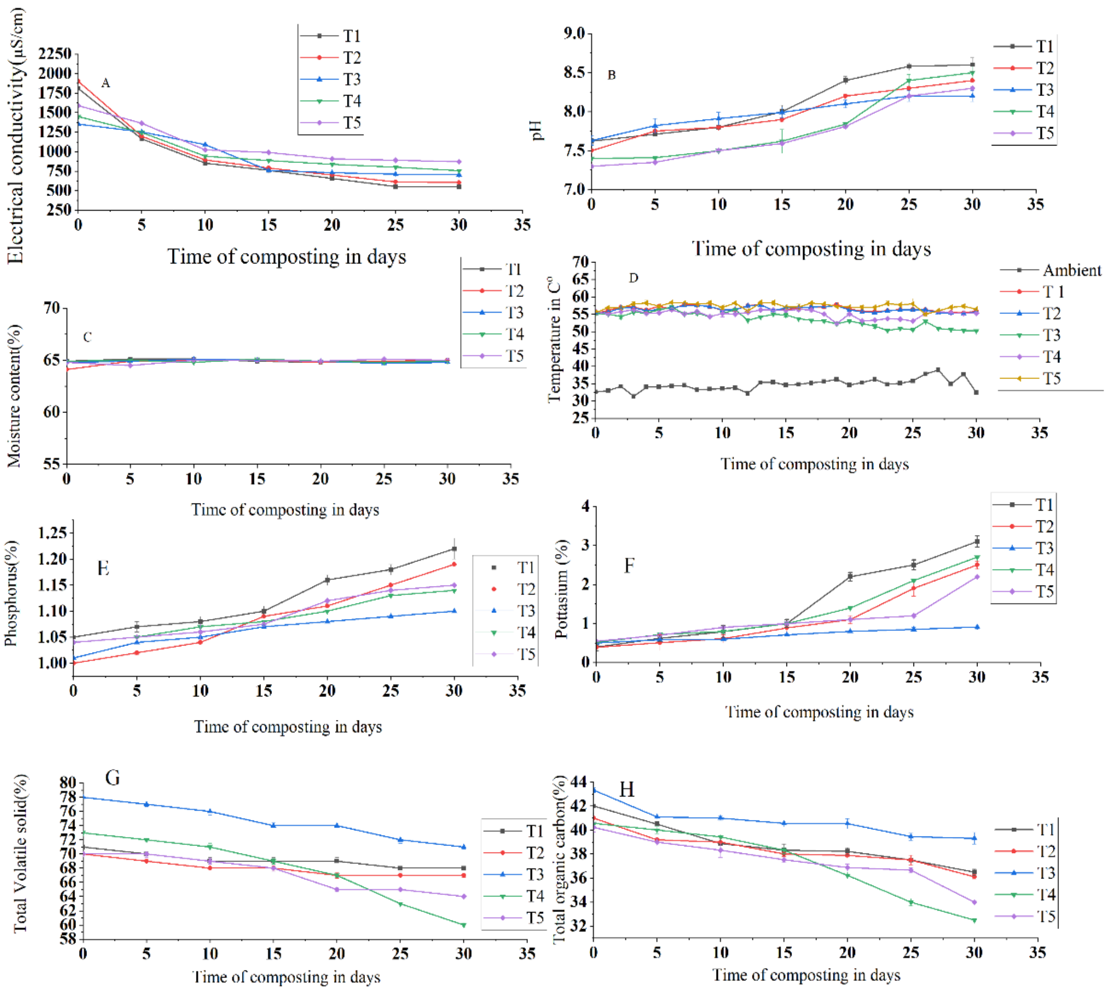

Figure 3. Variations of (A) Electrical conductivity, (B) pH, (C) Moisture content, (D) Temperature, (E) Phosphorus, (F) Potassium, (G) Total volatile solid, (H) Total organic carbon

The phosphorus content is one of the main factors in composting because it plays a major role in indicating ATP synthesis and microbial metabolism. The results for phosphoruscontent after 30 days of composting periodshowed an increase between 1.1 mg/kg and 1.2 mg/kg, in all different treatments, from T1 to T5(Fig.3(E)). The initial phosphorus level in the materials plays an important factors affecting final P content in compost [22].

Potassium (K) is an essential microelement for all crops useful to regulate the water pressure balance of plants and participate in photosynthesis. The percentage of potassium content increased proportionately in every trial (T1, T2, T3, and T4) (Fig. 3(F)). This increase is accounted for by both concentration effects on organic decomposition and mass loss [23]. Common initial potassium contents for trials were around 0.55 mg/kg; on execution of composting period, it had reached 3.1 mg/kg in trial T1 and a minimum value of 0.9 mg/kg at final was found for T3. Doses in trials T4 and T5 varied from 0.59 mg/kg to 2.7 mg/kg & 0.59 mg/kg to 2.2 mg/kg, respectively.In addition, this variation can serve as an indicatory on quality and nutrient stability in compost.

Total volatile solids(TVS)

TVS content of organic matter, which will begin to static at 550°C.About in five tests, trial T1, T2, T3, T4 and T5 the respective value is shown to reduce progressively (Fig. 3(G)). At first the strong value given off by T3 was still 78, which subsequently fell to 71 %. The TVS value of T1, T2, T4, and T5 fluctuated between 72% and 64%. Since these organic matter accumulated value without heat. This trend which prevails in all tests [24] and can be accounted for by the fact that temperature had been worked on right from start of the experiment. The Total Organic Carbon (TOC) is an important parameter in the decompostion of compost, the quantity of carbon involved in organic components as conclude form feed.

The results of T1-T5 for TOC in each of these experiments were all in decline. T3 had highest carbon content, at 43.33 % while T5 on the other hand showed lowest with a number of 40.23 % among measured values altogether.T4 in its outcomes came to a minimum of 32.5 %, which must be attributed to the use of inoculum and in shrunk leave biomass for T1, T2, T4 and T5. All these tests show falling values (Fig. 3(H)); only T3 results are very irregular. The TOC content falls as the microorganisms utilize carbon and themselves decompose organic matter into water (H_20) and carbon dioxide (CO_2), along with many stable organic compounds [25, 26].

3.2 Carbon nitrogen ratio (C/N ratio), Nitrogen content, Lignin, Cellulose, Hemicellulose, Ash, Ammoniacal nitrogen, Calcium

Nitrogen is an important factor in composting; the breakdown of organic matter and the overall efficiency of compost rely on nitrogen. The nitrogen content of the material has a significant effect on microbial activity. However, it is required to grow bacteria, which degrade organic matter. Percentage nitrogen concentration began to increase in all studies. At the beginning of all experiments the nitrogen concentration was about 0.65 percent, and rose progressively as the trials went on. The percentagesfor T1 through T5 are shown in Table 3.1 and Fig. 4(E). The high nitrogen content of T3was particularly in evidence (Fig. 4 (E)). Research has verified that maintaining proper (C/N) ratio can be a significant criterion. A suitable nitrogen content can be secured when the C/N ratio is brought to 25:1, the most suitable ratio [5].

There presents the carbon-nitrogen ratio balance of a material for compost, denoted, that is, how much of carbon or nitrogen. For each test, T1, T2, T3, T4 and T5, the C/N ratio showed a marked decrease. T3 was actually at first 69.66, but because of more brown material (Table 3). Eventually this value becomes 46.25. The C/N ratio for all experiments T1, T2, T4, and T5, experienced an decrement due to encouragement of microbial activity provided by shredded and grinded form of plant leaf biomass, to the point where it plunged between 68 to 26 (Fig. 4(F)). An effective C/N (Carbon/Nitrogen) ratio was found. Extremely high carbon-to-nitrogen ratios in composting are correlated with long periods of composting, resulting in delayed compost events. An inadequate percentage of C/N (with lots more nitrogen), can raise a complex ammonia catastrophe, wastage of volatilization losses by nitrogen.

Calcium (Ca) is an essential constituent of compost which is vital for both soil structure and plant vigor. Additionally, calcium raises the microbial decomposition efficiency of organic waste and also adjusts pH during composting. In addition, it stabilizes the finished compost through promoting aggregation into humiclike substances. That way you not only increase air flow but at the same time can improve structure of the richest garden loams as well as most nutrient poor soils. It was depicted in some titration procedures performed at laboratory facilities [27]. With each experiment the levels of calcium showed an increase (Fig.4 (H)). At 1198 mg/kg T1 was the peak value separated from starting content of 1010 mg/kg. T3 exhibited as much variation between 749 mg/kg to124mg/ kg. T4 and T5 rise and fell in their calcium content throughout the year, as these two consisted largely of plants mainly bushes, from shade gardens. Consumption of garden waste with biological activity analogous to gluttony will achieve this concentration range. Calcium's presence in compost is beneficial for agriculture and horticulture, since it is necessary for root development, nutrient absorption and overall plant health [28].

It can be seen that the lignin content in every trial tended overwhelmingly to grow over time (Fig. 4(A)). T1, T2, T4 and T5 have seen significant reduction in the level of lignin, while T3 showed only minor declines in comparison to its pre-compost state at 13.2 % to just over 11 % [29] reported limited lignin disassembly in composting systems with poor aeration, diverse microorganism populations and suboptimal conditions but in T1, T2, T4 and T5, the lignin concentrations fell from 13 % to only 0.3 %. Higher temperatures and the presence of special microorganisms help to make lignin degenerate, as seen by this significant decrease. Along these lines, has it also been proven with reference to oxygen supply anecdotes from [30] give some insight into this.The disparities in lignin reduction among every trials indicate that particular microbial populations and environmental conditions significantly influenced the differing results.

The degradation of cellulose is a crucial indicator of degradation in the processes. The content of cellulose exhibited the smallest variation in trial T3, decreasing from 43.5% to 39.1%, however in trials T1, T2, T4, and T5, the value significantly diminished within the range of 43.60% to 3.90% (Fig. 4(B)). The temperature controlled experiment revealed a significant reduction in cellulose content after 10 days from its initiation. The reduction in cellulose in every trials, along with the enzyme activity of the compost and microbial quantity, facilitates cellulose decomposition [31].

Hemicellulose, also known as polyose, is a heteropolymer that occurs with cellulose present in the cell walls of all terrestrial species of plants. Hemicellulose decreased in every trials, ranging from 10.5% to 0.5%, indicating the effect of inoculum during the thermophilic phase facilitated by temperature regulation in the reactor, except for T3, where a minor reduction in hemicellulose percentage was noted. In the instances of T1, T2, T4, and T5, the value experienced a sudden decline during the heating and thermophilic phases, initially occurring rapidly but thereafter decelerating (Fig. 4(G)).

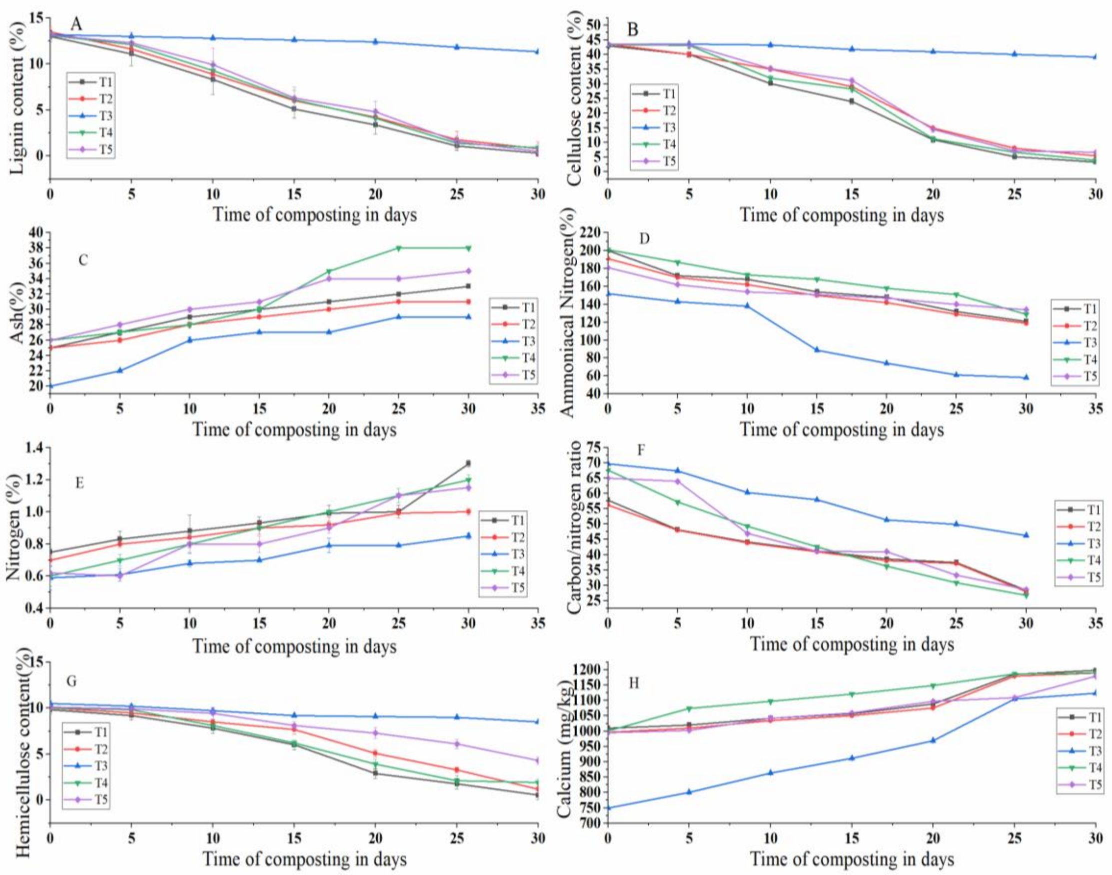

Figure 4. Variations of (A) Lignin content, (B) cellulose content, (C) Ash content, (D) Ammoniacal nitrogen, (E) Nitrogen, (F) Carbon/nitrogen ratio, (G) Hemicellulose content, (H)Calcium content

In order to estimate the ash content, a dried compost sample is typically incinerated at a temperature (usually around 550°C) to oxidize organic materials and leave only the inorganic minerals behind. Because the ash percentage peaked during the thermophilic phase, it increased somewhat across all trials (Fig. 4(C)). The Ash percentage varied from 25 % to 33 % in T1, from 25 % to 31 % in T2, from 20 % to 29 % in T3, from 26 % to 38% in T4, and from 26 % to 35% in T5. As a result, T4 had the highest amount of ash, which is likely due to microbial activity and feedstock composition [12].

Ammoniacal nitrogen comprises ammonia (NH_3) and ammonium ions (NH_4+). It acts as a gauge for the quality and maturity of compost. Compost's ammoniacal nitrogen content must be below 400 mg/kg to ignore detrimental result on crop productivity & safety [32]. Every trials demonstrated a progressive decrease in ammoniacal nitrogen percentage (Fig. 4(D)), indicating that the composting process was effective, resulting in the majority of nitrogen ina stable form. The values at the conclusion of period in trials T1, T2, T3, T4, and T5 were 121 mg/kg, 119 mg/kg, 58 mg/kg, 129 mg/kg and 134 mg/kg respectively. This also indicates that the entire process was executed with adequate moisture, aeration,regulation, and maintenance of the carbon-to-nitrogen ratio, among other factors. The initial & final value of various parameter is mentioned in table S2and anova table of its variation is mentioned in table S1 (Supplementary S1 and S2).

3.3 Parameters of seedlings (Fresh weight rice seedling, Root length, number of leaves, Growth of rice height)

Good quality rice seeds, specifically Pusa Basmati Rice, were utilized to assess the compost efficiency obtained from several studies. A stainless steel dish measuring 0.4 meter x 0.4 meterwas needed for the experiments. Hydrogen peroxide was necessary for sterilization, whereassoaking was done using distilled water (Fig. S1). Anincubator was utilized for experimentation within a temperature-controlled environment. A length& weighing scale were employed to measurethe seedling parameter.

Root length is a crucial seedling feature for any crop, serving as a conduit for nutrient absorption in plants. Nine day after plantation, T1 had the greatest root length of 6.2 cm, while T3 displayed the least root length of 5.7 cm. Throughout every trials, root length exhibited a progressive increase, peaking at 8.9 cm for T1. In contrast, T2 ranged from 6 cm to 8.5 cm, T3 from 5.7 cmto 8 cm, T4 from 6 cm to 8.9 cm and T5 from 6 cm to 8.5 cm (Fig. 5(D)). Diverse contaminants can harm plant cells and impede root development [33].

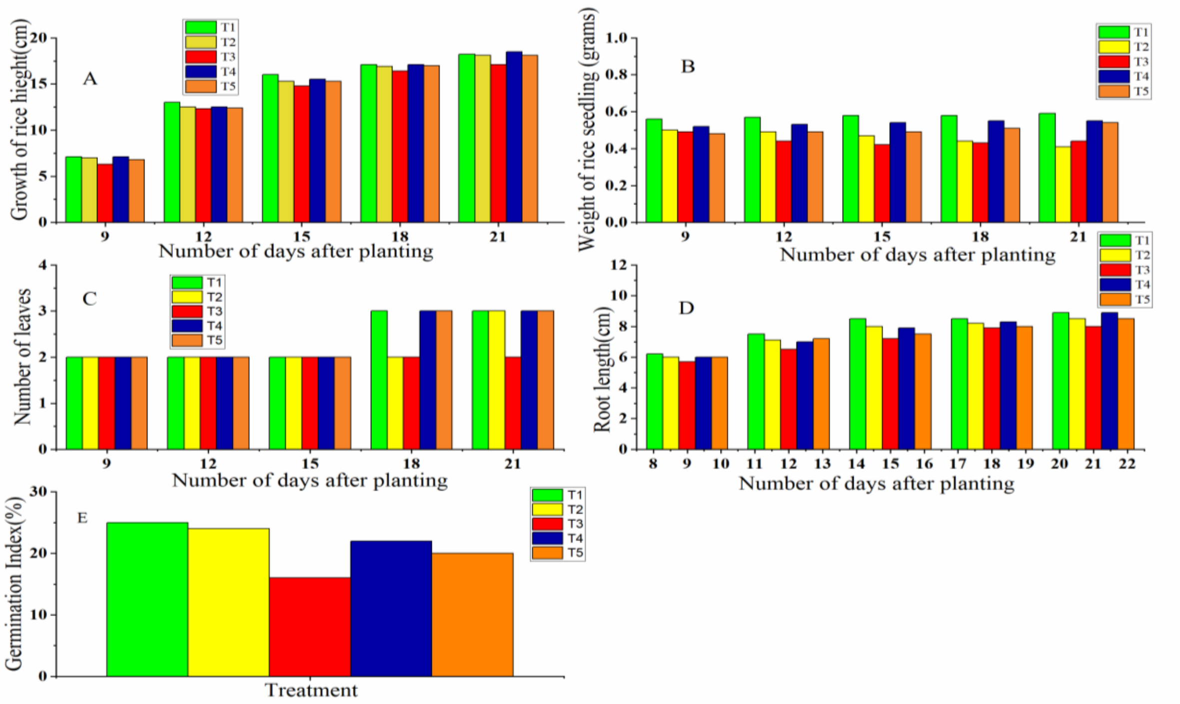

Figure 5. Variation of (A)Rice height growth, (B)Weight of rice seedling, (C) Number of leaves (D) Root length, (E)Germination Index

The rice seedling's fresh weight is a metric that indicates the health and their quality implications of their ingestion. The initial weights for every trials T1, T2, T3,T4, and T5 were approximately identical; nevertheless, with further observation at designated intervals, they all exhibited a progressive increase. The T1 sample attained a mass of 0.59 grams, T3 recorded a minimum mass of 0.44 grams, while T2 and T4 achieved masses of 0.55 grams and 0.54 grams, respectively (Fig. 5(B)).

No substantial difference in leaf count was seen across every trials T1, T2, T3,T4, and T5. T3 exhibited the lowest number of leaves, but T1,T2, T4, and T5 demonstrated a comparable quantity of leaves (Fig. 5(C)).

Similarly,the growth of rice height was monitored on a regular basis.It is a sign of effective nutrient cycling and high compost quality.The trials T1 reflected the maximum plant height since the beginning and ended up with a length of 18.2 cm on the last day of observation as expected as the trial T1 composed of compost made up of grinded plant leaf biomass and inoculum. A significant reduction in ammoniacal nitrogen (121 mg/kg), which falls well below phytotoxic thresholds. Lower ammoniacal nitrogen reduces toxicity risks to seedlings and enhances nutrient uptake. Additionally, the lowest electrical conductivity (0.549 mS/cm) recorded in T1 indicates reduced soluble salt concentration, which is critical for preventing osmotic stress during seed germination. These major combined effects reflected the most biologically stable compost. This compost T2 remarked its second position with the length of 18.1 cm on the final day of composting. T4 & T5 reflected almost similar results in terms of growth of rice height while T3 showed the least development of rice height of 17.1 cm (Fig. 5(A)).Similarly,the overall germination index percentage of all the trials was evaluated (Fig. 5(E)) [34].

3.4. Correlation Studies of Comparison to Global Benchmarks and Physico-chemical Parameters

To mention the most important relationships between physicochemical parameters, Pearson's correlation analysis was performed on 12 variables, creating a bar scale heat map as presented in Figure 6.

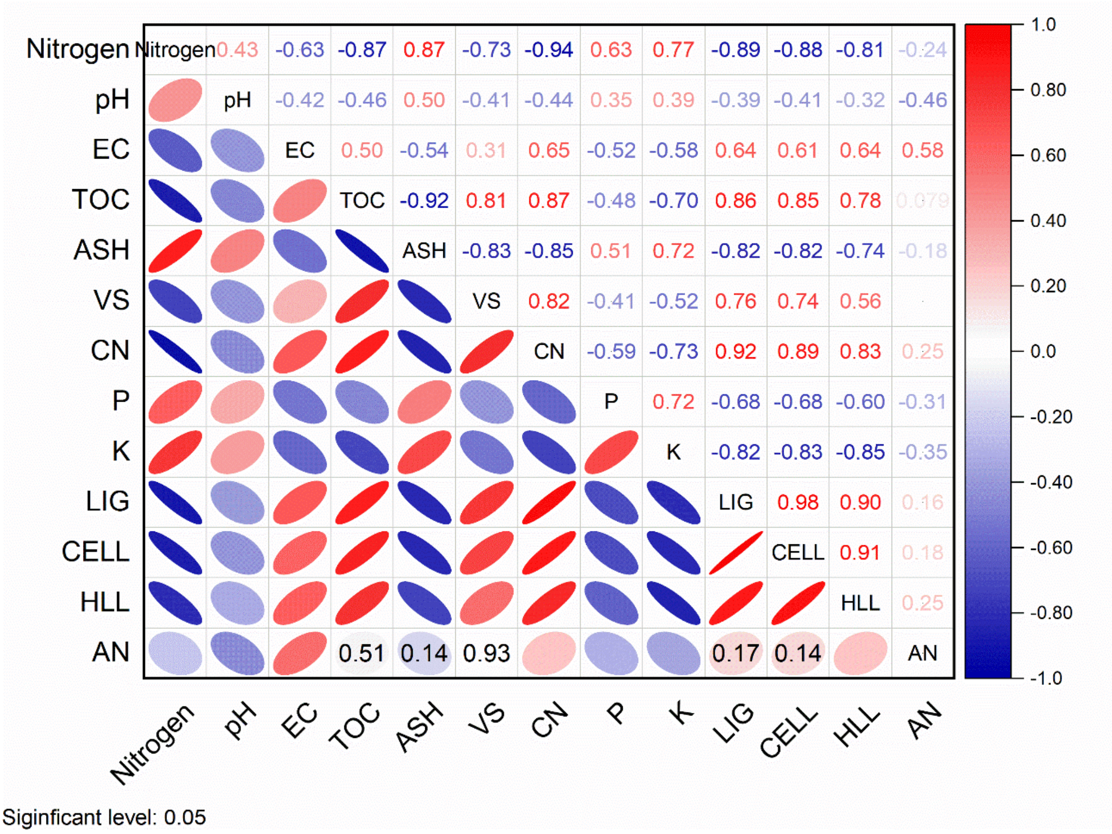

Figure 6. Correlation plot of Pearson's correlation coefficients of every parameters at significance level p<0.05 in which the circle size is proportional to the correlation strength.TN: total nitrogen, TK: total potassium, Temperature (TEMP), and electrical conductivity (EC), TP: total phosphorus, C/N: carbon-nitrogen ratio, CLL: cellulose; HEL: hemicellulose; LIG: lignin, Total volatile solids (TVS) and total organic carbon (TOC), ASH: Ash Content, NH4-N: ammoniacal nitrogen

The correlation for ammoniacal nitrogen content indicated that high temperature can increase the organic matter degradation with release of heat and carbon dioxide. There was positive correlation between electrical conductivity (EC) and total phosphorus (TP), total potassium (TK),total nitrogen (TN) and ash content of rock powder [35] proposed that plant tissue with higher nutrient and ash content would indeed have tend to adsorb more ions. Composting promotes the availability of nutrients (mainly N, P, K in the soluble form) through the breakdown of lignocellulosic materials, the plant cell wall's main components [36]. The microbes in the compost pile have a field day breaking down these complex structures, freeing nutrients for plant uptake.

Final compost's suitability is evidenced by fulfilling the world's compost standards such as Indian Fertilizer Control Order, 1985 [37] and, Organic Fertilizer Standard No. GB 18877–2009 issued by China [38]. Moisture plays an important role in the most appropriate handling of compost; excessive moisture makes compost heavier and handling difficult [39]. The pH values of all trials were within acceptable limits. There was also notice of reduced EC, possibly associated with changes in N, P, and K. Tukey's Honest Significant Difference (HSD) test at a significance level, $p < 0.05$ was performed regarding various parameters (Fig. S2 and Fig.S3).

3.5. Use of analytical hierarchy process (AHP) in in-vessel composting

The hierarchy used to score the composting trials is depicted. The AHP method was adopted for ranking the compost trials based on the following seven criteria considered significant for the maturation of compost: (1) number of days in the thermophilic phase, (2) pH, (3) electrical conductivity (EC), (4) total organic carbon (TOC), (5) Nitrogen content (6) carbon-to-nitrogen ratio, and (7) Ammoniacal Nitrogen (Figure 7).

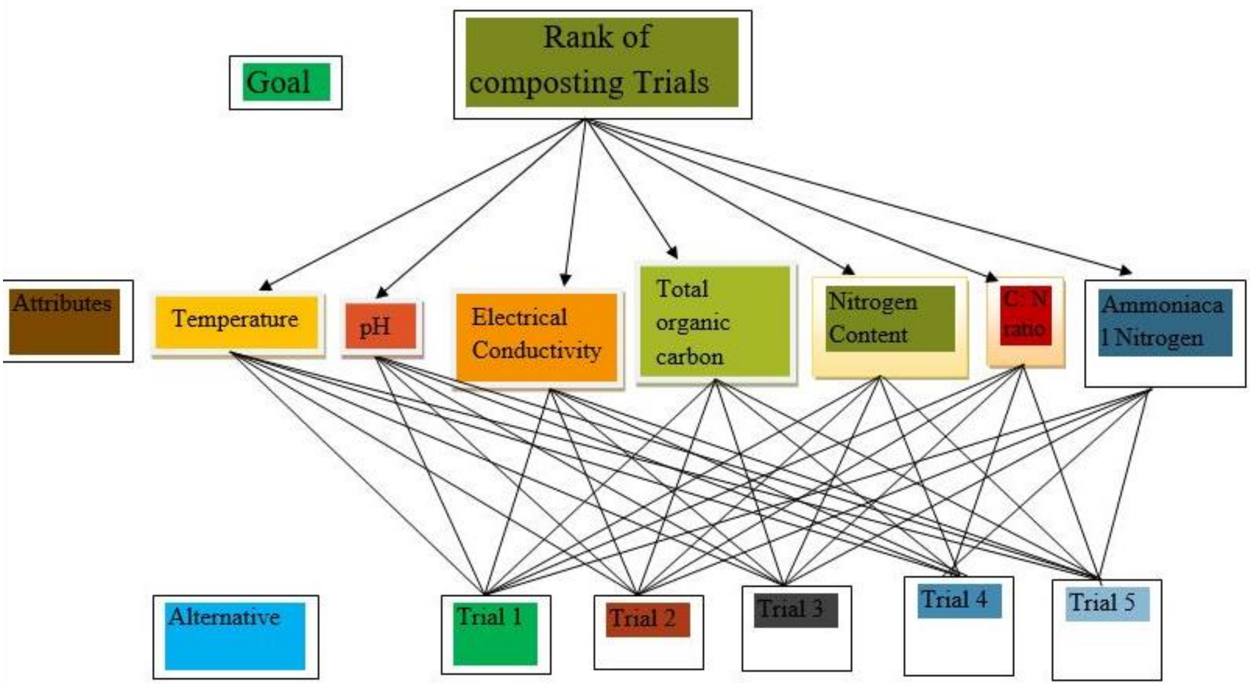

Figure 7. Ranking of composting trials in hierarchical form

The data from each trial's final 30 days of composting were used for ranking. The parameters are quality indicators of compost and the trials were optimized on these parameters by AHP. Alternatives and attributes are represented as a matrix (b), which is important for decision-making. After structuring the hierarchy, the weights were calculated using AHP with the acceptance based on the ratio of consistency. The quantitative data in normalized form is shown below, where using normalized data along weight indicates the ranking of alternatives.

The selected qualities are assigned intensity points using a nine-point intensity scale. A pairwise comparison was used to establish the relative significance of qualities scored on the nine-point intensity scale. AHP uses the consistency ratio (CR) to decrease inconsistencies in criteria weights. Eq. (1) is used to determine the consistency index (CI) prior to calculating the consistency ratio.

The CR value should be less than 0.1 to validate the weights and completes criteria of the pairwise comparison matrix. In this situation, CR=0.092, which is CR < 0.1, indicating validation of weights and consistency of matrix. Matrix A1 shows the pair-wise comparison matrix for the criteria listed below.

$$CI = (\lambda_{max} - M) / (M - 1) \quad (1)$$

λ_{max} represents the matrix's maximum eigenvalue. λ_{max} is the average of matrix A4 and M is the matrix's order. In this case, λmax is 7.748 and M is 7. (Matrix a).

3.5.1. Normalized data

All seven characteristics' normalized values are shown below. It was determined that the temperature (temp) function was the most beneficial and optimized. Temperature determines all other characteristics, such as pH, EC, C/N, TOC, and others, which either rise or fall with temperature. All other parameters were therefore normalized [41].

During the initial days, every reactor remained in the thermophilic phase.

3.5.2. Selection index

The best choice is determined by ranking the options using the selection index (SI)(Table 4(C)).A better rating is implied by a higher SI. It was computed by multiplying weight (MAT(A2)) by normalized data for all attributes. Among all the trials, Trial 1 had the highest SI rating (0.851), then after Trial 2 (0.832), Trial 4 (0.794), Trial 5 (0.781), and Trial 3 (0.759). The findings indicate that, out of all the experimental trials, Trial-1, which consists of grinded plant leaf biomass with organic inoculum, is the most effective combination.

Table 3. Evaluation of theAHP method, Matrixes

(a) Weights of criteria and Pairwise comparison matrix

Matrix (A1)

Attributes	Temperature	pH	Electrical conductivity	Total Organic Carbon	Nitrogen	C/N	Ammoniacal Nitrogen
Temperature	6	7.0	6.0	5.0	4.0	5.0	6.0
pH	0.14	1	1.50	0.10	0.20	0.35	0.19
Electrical Conductivity	0.17	0.6	1	0.20	0.19	0.15	0.33
Total Organic Carbon	0.20	10	5	1	0.99	3	2
Nitrogen	0.25	5	5.26	1.01	1	2	3
C/N ratio	0.20	2.8	6.67	0.30	0.50	1	3
Ammoniacal Nitrogen	0.17	5.2	3	0.5	0.3	0.3	1

The above table represents a pairwise comparison matrix developed to evaluate the relative importance of key physicochemical parameters. The selected criteria of temperature, pH, electrical conductivity (EC), total organic carbon (TOC), nitrogen, C/N ratio, and ammoniacal nitrogen are systematically compared against each other. The value of matrix reflects dominance of a parameter over another, value greater than unity reflects higher importance. The priority weight are illustrated in column of matrix A2 which is noted below, it was calculated using the geometric mean approach. Overall the computed weights showed that the temperature is the most dominant parameter in biological activity regulation whereas among the chemical parameter nitrogen and total organic carbon showed high significance reflecting their importance in organic matter degradation.

	Matrix (A2)		Matrix (A3) = Matrix (A1) * Matrix (A2)			Matrix(A4) = Matrix (A3)/Matrix (A2)	
Temperature	0.416		3.331			7.99	
pH	0.030		0.236			7.74	
EC	0.029		0.226			7.75	
TOC	0.175		1.345			7.66	
Nitrogen	0.165		1.192			7.18	
C/N ratio	0.107		0.837			7.79	
NH_4N	0.074		0.572			7.67	

(b) Alternative and attributes used in selecting

Attributes

Alternative	Temperature	pH	Electrical Conductivity	Total Organic Carbon	Nitrogen	C/N	Ammoniacal Nitrogen
Trial 1	4	7.3	0.5	34	1.3	26.15	121
Trial 2	6	7.1	0.6	29	1	29	119
Trial 3	7	7.5	0.7	26	0.85	30.58	58
Trial 4	5	7.4	0.75	22	1.2	18.3	129
Trial 5	4	7.4	0.87	22	1.1	20	134

(c) Selection Index and Normalized value

Attributes

Alternative	Temperature	pH	EC	TOC	N	C/N	NH_4N	Matrix(A2)	Ranking
Trial 1	0.5000	0.9	11	0.97	0.013	0.49	0.001	0.416	.851
Trial 2	0.7500	1.0	9.1	0.87	0.010	0.44	0.001	0.030	.832
Trial 3	1.1429	0.9	7.8	0.78	0.008	0.42	0.002	0.029	.759
Trial 4	0.5000	0.9	6.3	.66	0.011	0.65	0.001	0.175	.794
Trial 5	0.4000	0.9	6.1	.55	0.010	0.54	0.001	0.165	.781

As per AHP methods the ranking of piles are as follows: Trial 1-Trial 2-Trial 4-Trial 5-Trial 3. Among everytrials 1 to 5, Trial 1 has achieved first rank practically.

3.6. Statistical analysis using ANOVA

One-way analysis of variance(ANOVA) was done for testing the composting parameters statistically by using SPSS 13.According to the table S1, the specifically significant variation were observed in majority of parameters like nitrogen, pH, TOC, ash, volatile solid, C/N ratio, phosphorus, potassium, lignin, cellulose, hemicellulose etc reflecting its authencity.

4. CONCLUSIONS

In this study, the effect of type of plant leaf biomass with an inoculum on composting process in in-vessel reactor system were investigated. The main goal was to investigate the effect of the inoculum on the improvement of the compost quality and maturity. The results strongly indicate that the efficiency of the inoculum is greatly improved when applied in bothfinely grinded and shredded plant leaf biomass, of all the treatments, T1 showed the best performance in composting and obtained the best quality of compost.

This was evident in its highest rank in the AHP evaluation and in its compost's final characteristics like (organic carbon content of 36.5%, Nitrogen content of 1.3%,potassium content of 3.1 % and pH of the compost in the basic range. On the contrary, the poorer results in T3 indicate the limitation of plant leaf biomass not subjected to a previous shredding in the efficient breakdown by microorganisms and lengthening of the composting process as the unshredded biomass had lower surface area and higher porosity. The in-vessel composting system was important for the period of the active degradation of the material due to the maintenance of the temperature, which allowed the microbial activities to become effective and break down the organic matter. Overall, the importance of biomass pre-treatment (grinding/shredding), especially grinding and inoculum application, to maximize composting efficiency and quality, was stressed in the study. Further there is enough scope regarding improvement of organic inoculum efficiency as well as the main instrument ecoleaf composter inrespect of its design, working efficiency & scalability to handle the common problem at residential, urban and municipal level, as if now as indicated from this study ecoleaf composter can work efficiently for small residential societies.

Findings provide useful information for the optimal operation of composting systems, particularly for plant leaf biomass if used as a maximal feedstock in the controlled and in-vessel composting methods.

Appendix A Supplementary data

The following supporting information are there Table S1:Anova table for variation of all parameters, Table S2: Initial and Final value of various parameters, Figure S1: Seeds Growth from scratch after anti-fungal treatment and its parameter analysis, Figure S2: Tukey's Honest Significant Difference (HSD) test at a significance level, p <0.05 to find significant and non-significant differences between means of different pairwise comparisons of treatments of C/N ratio (A), total volatile solid (B), potassium (C), lignin (D), cellulose (E) and hemicellulose (F), Figure S3: Tukey's Honest Significant Difference (HSD) test at a significance level, p <0.05 to find significant and non-significant differences between means of different pairwise comparison of treatments of phosphorous (A), pH (B), nitrogen (C), electrical conductivity (D), total organic carbon (E) and total ash content (F).

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IZVOD

EFIKASNO UPRAVLJANJE BIOMASOM BILJNIH LISTOVA POMOĆU EKO-KOMPOSTERA ZA LISTOVE KORISTEĆI TEHNIKU STRUKTURIRANOG DONOŠENJA ODLUKA ZA OPTIMALAN IZBOR KOMPOSTIRANJA SUVOG LIŠĆA

Održivo upravljanje biomasom lišća, uključujući lišće, peteljke, grančice i druge nadzemne biljne materijale, postalo je značajan izazov kako u stambenim tako i u opštinskim uslovima. Eko-komposter za listove je razvijen kao održivo rešenje, a njegova efikasnost je procenjena kroz pet pokušaja (T1, T2, T3, T4 i T5) tokom perioda od 30 dana, pri čemu je svaki koristio različite oblike biomase biljnih listova. T1 je koristio mleveni oblik biomase biljnih listova sa organskim *inokulumom, a T2 je koristio mlevenu biomasu biljnih listova bez optimalne količine ručno napravljenog organskog inokuluma koristeći vredne sastojke. U T3 je korišćen neiseckan oblik biomase biljnih listova sa organskim inokulumom, dok je u T4 eksperimentisan usitnjeni oblik biomase biljnih listova sa organskim inokulumom, a u T5 usitnjeni oblik biomase biljnih listova bez upotrebe organskog inokuluma. Temperature kompostiranja održavane su između 50°C i 60°C, a sadržaj vlage je održavan na približno 65% tokom celog procesa. Analitički hijerarhijski proces (AHP) je korišćen za identifikaciju najboljih pokušaja. Među svim pokušajima, T1 je pokazao najveću efikasnost kompostiranja, sa pH opsegom od 7,6 do 8,6 (što ukazuje na aktivno kompostiranje), smanjenjem ukupnog organskog ugljenika sa 42% na 36,5%, povećanjem ukupnog azota sa 0,7% na 1,3% i smanjenjem odnosa C:N sa 57,8 na 28,3 tokom 30 dana. Takođe, sadržaj celuloze se smanjio sa 42,9% na 3,3%, hemiceluloze sa 9,8% na 0,5%, a lignina sa 13% na 0,3%. U poređenju sa T3, koji je napravljen od neselenog suvog lišća, ovo dovodi do sporije stope razgradnje, verovatno zbog velike veličine lisnog materijala. Zaključno, moramo imati na umu kako treba podesiti parametre kompostiranja kako bi se efikasno postupalo sa otpadom iz bašta. Ovaj pristup nudi alternativu tradicionalnim metodama odlaganja tako što pruža brz, kompaktan, in situ, ekološki prihvatljiv i efikasan pristup problemu.*

Ključne reči: *Eko-list, termofilna temperatura, održivost, cirkularna ekonomija, klijanje, suvo lišće*

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