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Pilot Design of Aerated Windrow Composting by Green Waste: A Step towards Sustainable Energy

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Abstract— Sustainable solutions are required to address the growing problem of solid waste management (SWM) in urban areas, especially in developing countries. The objective of this study is to treat organic solid waste (OSW) from academic institutions by investigating the design and development of an effective pilot plant for aerated windrow composting. The research looks on turning food waste from campus canteens into nutrient-rich compost at the Department of Chemical Engineering at the University of Karachi. Under carefully monitored circumstances, the aerobic aerated windrow composting process optimized critical parameters like temperature, moisture content, pH, and the carbon-to-nitrogen (C: N) ratio. Microbial activity produced a notable reduction in trash volume over the course of the 60-day composting period. The finished compost had a (C: N) ratio of 30.3:1 and an ideal organic content of 58%. The thermophilic phase was successful, as seen by temperature profiles, peaking at 65°C and facilitating efficient pathogen elimination and nutrient stabilization. Acceptable amounts of potassium (1.44%), phosphorus (1.3%), and nitrogen (1.1%) were found in the laboratory, along with a pH of 8.5. These findings highlight the promise of aerated windrow composting as an economical and green way to handle urban garbage in tropical regions.

The study concludes that implementing such composting systems in academic institutions can significantly mitigate the environmental impact of OSW. This research provides critical insights for policymakers and environmental engineers, supporting the development of large-scale composting initiatives to address waste management challenges in Karachi and similar urban environments.

Keywords: Composting, Aerated Windrow, Solid Food Waste, Inexpensive Alternative, Karachi.

I. Introduction

Waste management is a vital component of modern society on a global scale. Because of poor gathering methods and illegal disposal, managing waste is a critical issue that affects all kinds of communities. It is a challenging battle [1]. According to the UN Environment Program's (UNEP) Food Waste Report 2021, concluded 17% of the world's food output may go uneaten, with families accounting for 61% of this waste food, nutrition facilities for 26%, and markets for 13%. The goal of the UN Sustainable Development Goals is to reduce waste by half by 2023 [2]. By 2050, the amount of solid municipal waste produced globally will have increased by around 70%, to 3.4 billion metric tons [3].With the world's population approaching 8 billion, Solid Waste Management (SWM) is becoming a pressing worldwide issue, especially for underdeveloped and emerging nations [4]. Pakistan produces around 49.6 million tons of solid waste annually, with a 2.4% annual growth rate [5]. Over 20 million people live in Karachi, which produces more than 14,000 tons of municipal solid waste every day [6]. The global hunger situation has been made worse by excessive food waste, which amounts to around 1.3 billion tons year [7]. Solid waste is any unwanted material, part, or contaminated, drained, and polluted item that needs to be disposed of by the appropriate authority [4]. Municipal solid waste (MSW) composition differs from country to country based on factors such as average living standards, climatic conditions, cultural norms, and industrial and legal infrastructure are provided [8].There is still no proper method to reprocess the waste material from the solid waste [9].

There are several options available for disposing of solid waste e.g., incineration, sanitary landfills, and composting. Particularly in urban areas, solid waste incineration is an effective way of producing energy as well as reducing the trash volume that is growing at a rapid rate. Still, burning is costly, inefficient, and harmful for the environment. Hazardous air contaminants, such as nitrogen oxides, carbon monoxide, fine dust, and acid greenhouse gases produces from incineration causes cancer. In addition, combustion can also result in disruption, vibrations, odors, and water pollution, all of which can have a negative effect on the area around commercial and house. In recent years, landfills have emerged as one of the most common locations to dispose of waste. In nearly three-quarters of the world's countries, open-air dumps or landfills are the most frequent method of disposing of waste due to their low cost and limited technical requirement. Landfills produces an oxygen-deprived atmosphere, biogas and greenhouse gas emissions. In 2025, landfills will be estimated by the International Solid Waste Association (ISWA) to produce 10% of greenhouse gas emissions; if remediation is not carried out to regulate the release of biogas from landfills, this figure is going to maintain his increase [3].

The process of turning biological waste into a nutrient-rich soil amendment is called composting. In addition to being a sustainable and environmentally friendly method to reduce carbon-based waste, it can have other positive effects on the climate [10]. . Compared to conventional disposal techniques, it has a number of benefits, such as a 40–50% reduction in waste volume and the ability to eradicate microorganisms due to the heat generated during the thermophilic phase. Organic elements such as food waste, plant waste, water, and soil (which introduces helpful bacteria) are used in the process of composting. There are two types of composting process aerobic and anaerobic. Aerobic composting requires the introduction of air to break down each component. Anaerobic composting differs slightly from aerobic composting in that it does not require the addition of air. Aerobic composting is the decomposition of organic matter using microorganisms that need oxygen to survive, aerobes. Contrastingly, anaerobic composting happens with bacteria that do not require oxygen to live, anaerobes. Anerobic composting produces odors and lower heat generation requires more time for decomposition, requires additional heat and also produce sludge like material that is too difficult to disintegrate [11]. Aerobic composting is a self-heating process that breaks down organic waste by biological means. Compared to conventional disposal techniques, it has a number of benefits, such as a 40–50% reduction in waste volume and the ability to eradicate microorganisms due to the heat generated during the thermophilic phase. In this investigation, we concentrated on the process of aerobic composting.

The carbon-to-nitrogen (C: N) ratio, moisture content, particle size (degree of shredding), oxygen levels, pH, and temperature are important variables that affect the composting process. Temperature is the most important element affecting the quality of the finished product [12]. Furthermore, the fertilizer produced by composting is abundant in nutrients essential for robust soil and the development of plants. [13].

A lot of innovations done in the composting methods now the aerated aerobic windrow composting more advance due to its efficiency in treating organic waste. Using this technique, organic solid waste is mechanically turned into long rows, to guarantee an suitable supply of oxygen, which is necessary for the microbial decomposition process [3]. The composting process can be greatly accelerated by optimizing critical variables including temperature, moisture content, and microbial activity, as demonstrated by several studies on natural and controlled aeration techniques[14]. The use of aerated windrow composting in tropical settings is still not well understood, despite these developments. In particular, Karachi's metropolitan environment poses particular difficulties, such as high temperatures, fluctuating waste composition, and a lack of room for composting [15]

In order to fill this gap, this study looks into the planning and execution of an aerated windrow composting system that is suited for tropical metropolitan settings. This study demonstrates its uniqueness in addressing compost quality and process optimization in impoverished environments by contrasting the results with recent developments in composting technology.

Furthermore, because they promote the deterioration of organic materials, microorganisms play a crucial part in the composting process. Temperature and aeration can be adjusted in controlled circumstances to promote microbial activity and hasten the decomposition process [16]. Natural aeration systems, on the other hand, depend on the surrounding environment, which could lead to slower rates of degradation but provide a more affordable option for underdeveloped countries [17]. In regard to Karachi's environment, aerated aerobic composting techniques offer a framework for environmentally friendly waste management techniques in comparable a lot of urban environments [18] .

The purpose of this study is to investigate the treatment of organic waste generated at academic institutions through aerated aerobic windrow composting under controlled conditions. This research, conducted at the Department of Chemical Engineering, University of Karachi, aims to compare the composting efficiency, quality of compost produced, and environmental impact. By the assessment of variables like temperature profiles, carbon-to-nitrogen ratios, and compost maturity, this research will yield important information regarding the viability of large-scale composting in urban environments [19].

The main objective of this work is to design aerated windrow composting pilot plant to convert food waste generated from the different canteens of University of Karachi into fertilizer. Aerated windrows reduce construction costs and footprint by optimizing available area. The aerated windrow technology is one of the best economical solutions to protect the environment with respect to other technologies example incineration and landfills that create greenhouse gas emission.

The results of this study will be useful in developing waste management plans that, especially in educational settings, might lessen the negative environmental effects of organic solid wsate. The results of this study will provide valuable insights for policymakers and environmental engineers regarding the feasibility of executing extensive composting initiatives in urban places such as Karachi [4].

II. MATERIALS AND TECHNIQUES

Food waste samples, comprising fruit peels, damaged fruits and vegetables, paper, and wood, were collected from the University of Karachi canteens. To determine waste composition within the university, waste was collected from different canteens (Canteen A and Canteen B) over five days. The collected data is presented in Tables 1 and 2.

Table 1. Canteen A (CA) Waste Data (in kg)

Types of Waste Generated from Canteens of UOK	Day1 (Kg)	Day2 (Kg)	Day3 (Kg)	Day4 (Kg)	Day5 (Kg)	Total Waste Generated
C A						
Organic (A-O)	36.4	35	22.5	21	28.8	143.7
Inorganic (A-I)	13.5	10.8	8	7.2	9.2	48.7
Total (A-O +A-I)	49.9	45.8	30.5	28.2	38	192.4

Table 2: Canteen B (CB) Waste Data (in kg)

Types of Waste Generated from Canteens of UOK	Day1 (Kg)	Day2 (Kg)	Day3 (Kg)	Day4 (Kg)	Day5 (Kg)	Total Waste Generated
CB						
Organic (A-O)	22	20	19	19.8	21	101.8
Inorganic (A-I)	10	9	8	7.5	11	45.5
Total (A-O +A-I)	32	29	27	27.3	32	147.3

Composting requires the presence of two different types of materials. One is the carbon rich material and the other is nitrogen rich material. Depending on how good a compost product is required, these components ratios change. Usually, a ratio of approximately 1:3 [20]. The required nitrogen was supplied by food waste from the university canteens, and the required amount of carbon was raised by using hardwood chips and dry yard trash. The dried garden waste collected from the University of Karachi and sealed it in plastic bags.

The physical state, kind of composting system, and particle size all affect how wet a substance is when it comes to composting. The ideal moisture content is between 40 and 55 percent [20]. The aeration capacity level of the compost pile must not be <5%, optimal level of oxygen for compost pile is 10% [21]. In order to maintain the composting piles moisture content, water was added to the windrows. To guarantee a uniform distribution of water for moisture content and to give the windrow oxygen, or aeration, the pile was turned on a regular basis.

Depending on the stage, the ambient temperature varies dramatically during the composting process. Without external heating, the process can reach a maximum temperature of 65°C from its starting point at room temperature. The compost pile finally reaches room temperature during the maturation process. It is crucial that the temperature does not drop too soon since the prolonged high temperature encourages speedy breakdown and efficient sanitization [22].

pH has no effect on the composting process as long as it stays within the normal range that is present in combinations of organic materials. Higher pH levels, on the other hand, promote the conversion of nitrogen in organic molecules and cause ammonia volatilization, making pH more crucial in substrates rich in nitrogen. A pH of 5.5 to 8 is good, with levels around neutral being best for microbial activity. Fungi can tolerate pH levels that are higher than neutrality, whereas bacteria can only survive in an almost neutral pH [23].

A pilot plant with a capacity of 1000 kg was designed based on the organic waste analysis from Karachi University canteens. The plant occupies a footprint of 20 × 2 ft. Figure 1 shows the windrow layout.

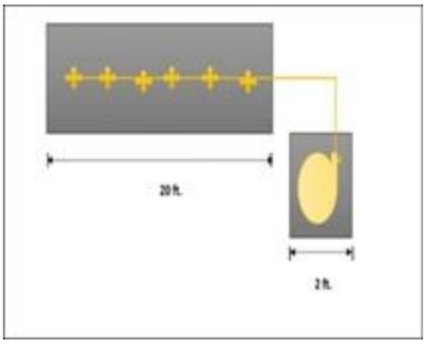

Figure 1: Pilot layout of windrow

Figure 2 illustrates the process of composting organic waste through aerated aerobic windrow composting. Here is a step-by-step explanation of the stages shown in the diagram. First of all, install an energy source with proper electrical wiring and a control panel for operating the blower system. The control panel will allow you to monitor and regulate the airflow. Attach cartridge filters at the blower's inlet to remove harmful airborne particles and ensure clean air is supplied into the pile, reducing dust and improving workplace safety. Then used a U-PVC pipe as an air diffuser, drilling 2 mm holes along its length to evenly distribute air into the compost pile. After that connect the blower's outlet to the U-PVC pipe using a flexible rubber pipe to ensure a tight connection and smooth airflow. Lay the U-PVC pipe on a bed of crushed stones to prevent it from being trapped or blocked by the soil, allowing even air distribution and supporting the airflow system.

After that consist of organic waste, such as fruit and vegetable scraps, is collected from the different canteens of

Karachi University is one of the primary raw materials for composting. Another essential raw material used in the composting process is wood chips and garden waste taken from Department of Chemical Engineering University of Karachi. These materials provide the necessary carbon content and structure to the compost pile, ensuring proper aeration and preventing compaction. Then organic waste (both fruit/vegetable waste and wood chip/garden waste) is mixed together and arranged into long, narrow piles called windrows. A 3:1 ratio of food waste (400 kg) to yard waste (100 kg) was maintained. Windrows are an efficient way to compost large amounts of organic material, as they allow for better aeration and management of the decomposition process. After the windrows are formed, they are covered with perforated fabrics. Covering helps in maintaining moisture levels, protects the compost from external weather conditions, and ensures that heat generated from the microbial activity is retained.

The pipes deliver oxygen to the pile, aiding microbial activity and accelerating the decomposition process. The positive pressure aerated blower should run continuously at around 25-30% efficiency, ensuring a consistent supply of air throughout the composting period. In order to obtain a representative profile of the composting pile, hygrometers and calibrated digital thermal sensors were positioned at three key locations within each windrow to measure the temperature and moisture content. To guarantee uniformity in the composting process, data was taken twice a day. The sensors were placed in three different locations: (1) in the middle of the pile to track core microbial activity, (2) close to the top to evaluate interactions with the outside environment, and (3) at the bottom to identify any moisture buildup. Trends and deviations necessitating remedial measures, including modifying aeration or moisture levels, were identified through the analysis of recorded data. Manually add water as needed to maintain the moisture content between 30-60%, which is critical for microbial activity and decomposition.

Water content is important because bacteria need water to use the dissolved nutrients [16]. The mixture was moistened with regular tap water, whose properties are presented in Table 3.

Table 3: Properties of Water Used in Composting

Parameter	Values
Ph	6
Hardness (as $CaCO_3$) mg/l	160
Total dissolved solids (TDS) mg/l	210

After 2.5 months, once the compost is ready, use a Vibro Mixer with different mesh sizes (1-8) to separate the fine compost from larger particles or contaminants that might need to be composted again. Finally, compost samples sent to the laboratory for analysis.

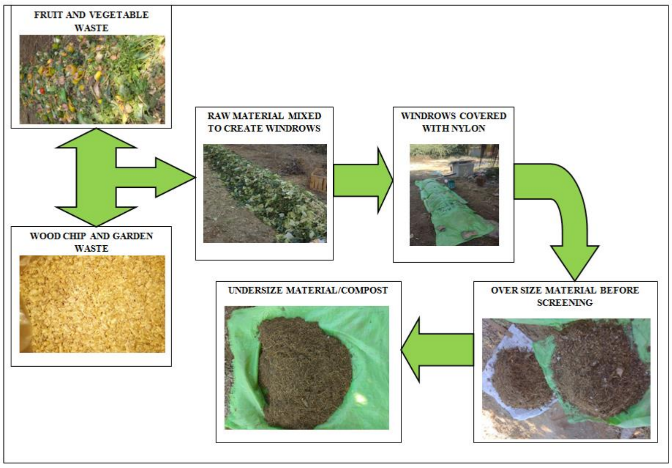

Figure 2. Aerated Windrows Composting Process

Brown humus material emerged in the aerated windrow after 2.5 months, the dark, organic component signals that the process of composting has completed as depicted in figure 3.

Figure 3. Final Compost

III. RESULT AND DISCUSSION

Result obtained after composting from the Pakistan Council of Scientific and Industrial Research (PSCIR) laboratory analyzed the compost for moisture, pH, carbon, phosphorus, nitrogen, potassium, and calcium content. The C/N ratio was calculated from the carbon and nitrogen measurements. PCSIR uses two methods first one is Standard Methods for the examination of Water and Waste Water, 20th Edition, American Public Health Association and second one is Test Methods for the Examination of Composting and Compost USDA and US Composting Council, 2002. The results obtained were compared to other production systems assembled information from many sources [24]. Every test was run in accordance with established standard operating procedures.

The compost testing results are shown in Table 4. This table shows the chemical parameters (pH, EC, total organic carbon, total organic matter, total nitrogen, total phosphorus, total potassium, and C/N ratio) of the compost to those obtained by other studies and demonstrates that the compost satisfies standard compost quality.

Table 4: Chemical Composition of Compost with Benchmark Comparisons and Statistical Analysis

CHEMICAL ANALYSIS	RESULTS	Ideal Range	Deviation	Significance (p-value)
Moisture	45%	30-60%	Within Range	Not Significant
Organic Content	58.0%	40%-60%	Within Range	Not Significant
Potassium as K2O	1.44%	0.5-2.0%	Within Range	Not Significant
Phosphorus as P2O5	1.3%	0.2-3.0%	Within Range	Not Significant
Carbon	33.33%	15-35.1%	Within Range	Not Significant
Nitrogen	1.1%	1.0-1.0%	Within Range	Not Significant
pH	8.5	7-8.5	At Upper Limit	Marginally Significant
Electric Conductivity	9.33ms/cm	1-9 ms/cm	Exceeds Limit	Significant ($p < 0.05$)

Upon completion of the composting process, a notable decrease in both volume and mass was noted. The volume of the compost material was reduced by 60%, according to the results reported on a dry basis.

After 60 days period of composting, the organic waste was tested for the moisture content that showed the product had 45% moisture as shown in the table 4. The moisture content is just lower than the 50% recommended limit for fertilizer [25]. However, it is between the ideal ranges (40–60%) of compost that is good for a regulated composting treatment process.

In composting, microbial activity was well-supported by a pH in the range of 6.7-9.0 [26]. For the process of composting the pH value needs to be between 7 and 8.5 in order to satisfy the requirements for applying organic fertilizer [27]. The food waste and garden waste had an acidic pH of 4.8 at the start of the composting process. The process pH ranged low for the first 15 days, between 4.5 and 6. After 25 days, there was a noticeable increase in the waste pH, and after that, it varied betwee 7 - 8.5, until the 60-day process was completed. The pH is 8.5 as shown in the table 4 is under the composting process pH range.

A reduced amount of organic matter indicates the presence of produced organic materials, such as plastic and metal, and inorganic substances, such as sand, clay, and silt. Organic content determines the quality of the compost prepared [28]. Due to the presence of food waste, the proportion of organic content in the compost was found to be 58%. The nutrients found in organic matter help to maintain soil health and promote plant growth by enhancing microbial activity, soil structure, and water retention.

Microorganisms in the composting process mainly get their energy from carbon. A high level of carbon encourages the decomposition of organic matter and helps preserve the structural integrity of compost. The carbon content of compost plays a critical role in microbial activity and overall decomposition efficiency. Carbon is the primary component of a microbial cell, making it a source of energy. As the composting process, less CO_2 is created and microbial activity declines, which lowers the carbon content [20]. It was discovered that the product had a carbon content of 33.33. The values for total organic matter varied from 28.60 to 41.20 percent [12].

Nitrogen is essential for protein synthesis in plants and microorganisms. A proper nitrogen content supports microbial activity and accelerates composting. Nitrogen is utilized to determine the C/N ratio, in the composting process [20]. It relies on feed stock, the solid food waste utilized for composting is rich in nitrogen the amount present in the finished compost is also greater that is determined to be approximately 1.1%. The process of nitrification yields nitrite ($NO^{-}2$) and nitrate ($NO^{-}3$) whereas ammonification (NH_2 and NH_3) of the organic matter's total nitrogen content occurs during composting [29].

Solid food waste has a higher carbon to nitrogen ratio than municipal garbage; a higher C/N ratio denotes higher-quality compost [30]. Because of the greater C/N ratio, the rate of decomposition falls with very low quantities of food waste [31]. The results demonstrate that the created compost is of ideal quality, with a C/N ratio of 30.3/1. This is in line with previous research that indicates a C/N ratio of 20% or higher due to the influence of the C/N ratio of raw materials [30].

The increase in the phosphorus during composting was possibly caused by concentration effect arising from the higher rate of carbon loss that occurs when organic matter is decomposed [32]. Phosphorous is required for organic plant transmission of energy, growth and development of roots. Fruiting, flowering, and seed production in plants also increase agriculture productivity and promoting early plant maturity. The phosphorous content in compost generally ranges from 0.3-1.5% (P_2O_5 dry weight basis) influenced by the composting process and organic waste material [33]. Parameters like temperature, pH and moisture effects the concentration of the compost [32]. Potassium (K_2O) increasing the plants resistance to environmental stresses like diseases, enhancing cell wall and overall health of plants. Controlling the opening and closing of stomata which aids in the plant’s ability to water intake. increasing Photosynthesis of protein and carbohydrates. Compost typically contains 0.5-1.5% K_2O (dry weight basis) of potassium. Variation is dependent upon the decomposition process and the compost source material.

N-P-K compost results obtained are 1.1:1.3:1.44. Although compost has a lower N-P-K concentration than commercial fertilizer however, it can cause nutrient buildup in the soil when applied more regularly. Certain salts, such chloride and sodium, can be bad for crops that grow vegetables. But most compost has stronger electrical conductivity since it contains more nutrients, and at approved field rates, it does not contain enough of these salts to be phytotoxic [34]. Composting technique and feedstock can have an impact on the electrical conductivity of the material. The concentration of soluble salts from the breakdown of organic matter may cause the electrical conductivity of compost to increase during aerated windrow composting; yet, values in the range of 2-6 mS/cm are generally regarded as suitable for agricultural application [15]. The resulting compost's electrical conductivity (EC) was 9.33 mS/cm, which is higher than the permissible range of 2–6 mS/cm for agricultural uses. The buildup of soluble salts from the feedstock, notably sodium and magnesium ions, is probably the cause of this high conductivity. The compost's suitability for some sensitive crops may be limited by such high salt levels. Strategies like pre-leaching the feedstock, diluting with low-salinity organic materials, or modifying the C ratio can be investigated to lessen this problem in subsequent iterations. Further research ought to concentrate on improving feedstock management in order to reach EC values suitable for wider agricultural applications.

Thermal sensors were used to track the temperature during the 60-day composting period. In Figure 3, the temperature profile is displayed. This clearly demonstrates a standard temperature profile of an exothermic process [12]. Temperatures rise as a result of the highly active microbial process that breaks down organic material. According to the profile, there was a thermophilic phase during which the temperature fluctuated between 40 and 70 °C as a result of microbial degradation that began on the 15th day of composting and lasted for around 32 days. At the end of the 32-day period, the temperature dropped to between 20 to 40°C, signifying the mesophilic phase. This is because the activity of the microorganisms in the composting process decreased, marking the process's completion.

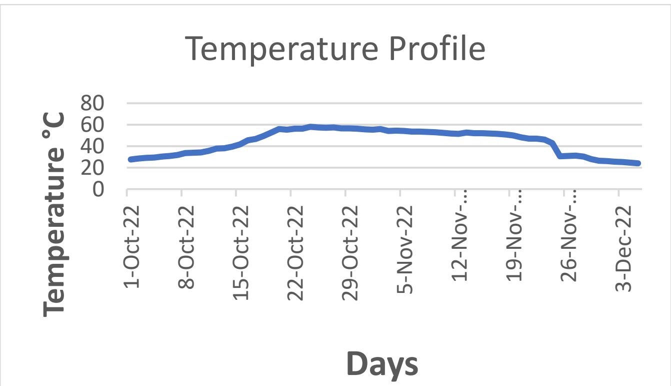

Figure 4. Composting process temperature profile during a 60-day period. The three separate stages of microbial activity are depicted in the chart: (1) the mesophilic phase, (2) the thermophilic phase (40–70°C), which aids in the removal of pathogens and the stabilization of nutrients, and (3) the last cooling and maturation phase.

Conclusion and Recommendations

This research highlights that composting is an effective alternative method for reducing the volume of waste generated by the canteens at the University of Karachi. The analysis revealed that the organic content of the compost is 58%, falling within the optimal range of 40-60% of ideal range of compost. The potassium content was measured at 1.44%, which is within the acceptable range of 0.5-2.0%. The phosphorus content, expressed as P2O5, was 1.3%, aligning with the standard test range of 0.2–3.0%, indicating an acceptable level. The carbon and nitrogen content of the compost were measured at 33.33% and 1.1%, respectively. The carbon content exceeds the standard value of 30%, indicating a robust decomposition process and providing energy for microbial activity [20]Meanwhile, the nitrogen levels fall within the ideal range of 1–1.5%, supporting efficient microbial metabolism and enhancing compost quality. In contrast, our results are consistent with research on tropical composting, where high ambient temperatures promote nitrogen stability while hastening carbon breakdown [31]. These features show how well aerated windrow composting works to create nutrient-rich compost in regulated settings.

The final pH of the compost material was recorded at 8.5, which meets the standard range of 7-8.5 for fertilizer application. However, the electrical conductivity was measured at 9.33 mS/cm, exceeding the acceptable range, which suggests a higher presence of salt ions, predominantly sodium and magnesium, potentially harmful to soil health. Although the compost generated in this study satisfies a number of quality standards, its high electrical conductivity (9.33 mS/cm) necessitates improvement for wider agricultural uses. procedures to lower soluble salt concentrations, like pre-treating organic waste and improving aeration procedures, should be investigated in future studies. With these enhancements, the composting process may become even more efficient for environmentally friendly urban garbage management.

The composting process effectively reduced the mass of organic waste by approximately 60%. Aerated windrow composting was chosen due to its ease and efficiency, with readily available materials. This method eliminates the need to turn the compost pile, resulting in no associated labor costs, making it a cost-effective solution. Throughout the composting process, there were no offensive odors, and emissions of organic compounds, greenhouse gases, and ammonia were minimal. Additionally, composting helps lower the costs associated with land procurement for solid waste treatment via landfills, reduces subsurface water contamination, and produces an environmentally friendly product that enhances soil health, plant vitality, and water retention.

There is a global change toward improving both human and environmental health. Composting, as a form of organic fertilizer, can significantly contribute to this goal. By prioritizing composting, can transition from chemical fertilizers to biological fertilizer that is compost, thereby decreasing the discharge of hazardous substances into the environment, ultimately benefiting both environmental and human health. Furthermore, composting offers the Sindh Solid Waste Management Board a sustainable solution for managing organic waste disposal without the issues associated with hazardous gas emissions or leachate affecting groundwater quality.

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