Tannery Liming Sludge in Compost Production: Sustainable Waste Management

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Research Article

Keywords: Wastewater, Compost, Hair burning liming sludge, Pollution, NPKS, Heavy metal

Posted Date: May 4th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-442633/v1

Abstract

In tannery at beamhouse, hair burning liming wastewater is the most toxic substance, which has adverse impact on the environment. Treatment of hair burning liming wastewater begets substantial amount of solid waste termed as 'sludge'. In this investigation, in-situ prepared liming sludge from hair burning liming wastewater is used for compost processing. The liming sludge is mixed with sawdust, cow dung, and chicken manure; piled onto a horizontal bamboo aerator. Three compost piles were built up weighing 650, 690, and 630 Kg. Drastic changes were observed in temperature due to the revolving of the piles. The highest temperature generated in the piles were in the thermophilic range at 59.69°C, 64.41°C, and 63.36°C respectively, ensures the destruction of pathogenic microorganism. The heavy metals Zn, Cu, Cr, Ni, Cd, and Pb of the compost were analyzed and the highest amounts found among the piles were 152.64, 21.20, 21.02, 6.93, 5.78, and 3.30 mg/kg, correspondingly. Moreover, the nutrient nitrogen, phosphorous, potassium, sulfur of the compost fulfills the requirement of the investigated material as compost. SEM analysis indicates the degradation of the composting materials. This study reveals that without any pretreatment, the generated tannery liming sludge can be transformed into a value-added product with the use of a zero-waste approach.

Highlights

- Toxic tannery liming wastewater management through composting
- Nutrient and metal content level of the compost found within standard limits
- Germination test indicates the compost suitability for soil conditioner
- Reduction of treatment load on effluent treatment plant (ETP)

Introduction

Recently, emphasis on environmental conservation through recycling or safe disposal of industrial waste has become a major concern, especially for the developed and developing countries. Reutilization of industrial waste and by-products are popularly being adopted throughout the world. This allows recycling the waste and neglected materials and thus reducing the amount of unusable waste exposed to the environment. The tannery industry uses the hide or skin of animals, the by-product of the meat industry, as its primary raw material. Different physical, chemical and mechanical operations are conducted during the manufacturing process to convert the hide and skin into leather. The tannery industry is criticized throughout the world for its extensive waste generation. There is ample opportunity to employ recycling and safe disposal practices in case of the wastes originated in tannery industries as well.

During the leather manufacturing process, the chemicals dissolve or eliminate the unwanted interfibrillary soluble proteins, hairs, epidermis layer, subcutaneous fat and fleshings before the start of the tanning process. The removals of these organic components from the hide/skin create openings inside the fiber hierarchy allowing tanning agents for penetration and reaction of tanning chemicals with the collagen fiber [1]. Liming is the first imperative chemical operation in the tannery where lime 'calcium oxide' (CaO) is utilized in combination with sodium sulfide (Na_2S) or sodium hydrosulphide (NaSH). The hydrosulfide breaks down the di-sulfide bond (S-S) of hair and the hydrated lime creates an aqueous buffer alkaline pH [1]. In high pH (pH 10-12) condition of hair burning liming operation the keratin as well as non-structural protein is dissolved, the collagen fiber bundles are split up and the natural fat is partially saponified [2, 3]. As a result, the wastewater stream from the hair burning liming operation contains protein, dissolved hair, lime, salt, fat, etc.

The discharged wastewater from hair burning liming contains a high amount of sulfide (S^{2-}), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total solids (TS), lime, etc. [4]. Usually, a measure of 30-40 m^3 wastewaters is discharged during the manufacturing of one ton hide/skin [5]. When this is combined and treated through a central effluent treatment plant (CETP), it produces 100-150 kg of sludge [6]. According to the analysis of Xu et al. [7], this indicates that for every ton of hides/skins processed, about 60-105 kg of liming sludge is produced.

This data is especially significant for the country as Bangladesh produces around 200 million sq. ft. of leather from 85000 tons of raw hide/skin per annum [8]. That means that around 5100-8925 tons of liming sludge is produced every year in Bangladesh alone. In Bangladesh, this alarming amount of sludge is generally dumped for landfilling and has no profitable application. The severity of this situation requires immediate action on the environmental damage or potential risks of this sludge landfilling, especially when it’s not in engineered landfills. Concerned researchers have developed several techniques for the treatment of liming wastewater [9-11]. The higher the pH and sulfide content in the sludge is, the higher is the demand for pre-treatment before further application and the higher is the process time and cost. Considering the amount of waste, this problem calls for a zero-treatment process to return this waste into the environment in a safe and sound way. This is why composting is considered a viable option.

Composting refers to the stabilization of organic materials through bacterial degradation under controlled aerobic or anaerobic conditions [12]. The microbial organisms deteriorate the organic components into hygienic, humus-rich bio-matured compost and generate heat as a metabolic waste output [13]. The generation of compost from industrial and municipal waste has become a very popular practice over the last few years [14-17]. Attempts have also been made to use tannery solid waste from the different operational stages for composting [18-22]; some of these processes require pre-treatment of the waste or are not industrially applicable.

An investigation was carried out by Xu et al. [7] that focuses on the hair burning liming sludge which is responsible for 60-70% of the tannery pollution load. The reduction of the waste load at this stage would make the treatment process more convenient, as well as produce a lower pollution load. While some researchers have previously tried to use combined tannery sludge for composting, the hair burning liming sludge method has yet to be applied for composting. This work will encourage the reutilization of the humongous sludge load into a novel value added product.

This study produces in-situ liming sludge from the toxic hair burning liming wastewater and then it composted with some other waste products in a pilot-scale without any pre-treatment. This research monitors the moisture, temperature, and other parameters at different time intervals to observe the changes in the compost. Moreover, the SEM and nutrient analysis assures the biodegradability and applicability of the compost.

Materials And Method

Composting Materials

Lime sludge preparation

In-situ liming sludge (LS) was prepared at Superex Leather Ltd., Khulna, Bangladesh. After the liming process, the liming wastewater was collected into plastic drums with a capacity of 125 L. Slowly, aluminium sulphate, $Al_2(SO_4)_3$ was added as a coagulant of the liming wastewater and continuously stirred. The pH was maintained at a range of 8.5-9.0 to prevent the generation of hydrogen sulfide (H_2S) gas from the liming wastewater [23]. After 6 h, the sludge settled at the bottom of the plastic drums. Gradually, the liquid was decanted from the top of the drums and liming sludge was collected in a gunny sack. Finally, the sludge was transferred to the laboratory for composting.

Collection of raw materials

To provide the necessary carbon to nitrogen (C/N) ratio in the liming sludge composting, sawdust (SD), chicken manure (CM) and cow dung (CD) were respectively collected from a sawmill, poultry farm and local dairy farm in Khulna, Bangladesh, in close proximity to the site of the experiment. As each of the components were waste matter from each sector mentioned above, it significantly reduced the cost of compost raw materials.

Seed collection

For germination test of compost, *Abelmoschusesculentus* seeds were collected from the local market in Daulatpur, Khulna, Bangladesh.

Reagents

For elemental analysis, the following several analytical reagent grade chemicals were used: sulphuric acid (H_2SO_4), potassium sulfate (K_2SO_4), cupric sulphate ($CuSO_4.5H_2O$), metallic selenium powder, sodium hydroxide (NaOH), boric acid (H_3BO_3), ammonium molybdate, ammonium vanadate, potassium di-hydrogen phosphate (KH_2PO_4), ammonium acetate, potassium chloride (KCl), calcium di-hydrogen phosphate ($Ca(H_2PO_4)_2.H_2O$), pure gum acacia powder, barium chloride ($BaCl_2$), potassium sulfate, barium sulfate, nitric acid (HNO_3), acetic phosphoric acid. The reagents were obtained from a local scientific supplies store.

Composting set up

Aerobic window composting was selected for this experiment to avoid the release of obnoxious gases and to reduce the experimental cost incurred for an anaerobic setup. To ensure oxygen supply, passive aeration was supplied to a horizontal frame made of bamboo. The bamboo frame with the dimension (L × W × H=105 cm × 245 cm × 138 cm) was used for the composting pile setup. Three separate composting piles (P#1, P#2, and P#3) were set up on the three bamboo frames. This setup does not require any energy-consuming air supplying system or any other control of the environment and is easily applicable even in remote parts of Bangladesh.

Sludge and waste materials piling

Three separate piles were constructed with different sludge and waste ratio to maintain the required amount of C/N ratio and other nutrients. For pile P#1, the compost mixture was prepared with 400, 60, 70 and 120 kg of liming sludge (LS), sawdust (SD), chicken manure (CM) and cow dung (CD) respectively with a gross total weight of 650 kg. For pile P#2 and pile P#3, the amount of LS, SD, CM, CD were 350, 70, 100, 170 kg and 350, 60, 150, and 70 kg, respectively. The raw materials and mixture of compost materials were characterized by physicochemical parameters. The three piles are shown in Fig. 1.

The compost piles were revolved when the temperature became stable or below the thermophilic range (<40°C) to ensure destruction of pathogenic organism, supply of good air and growth of microorganisms.

Physical & chemical analysis

At different stages, the physicochemical properties of the compost were evaluated for temperature, moisture, pH, electrical conductivity, salinity, total dissolved solids (TDS), dry matter, fixed solids, and volatile solids. The completion of biological and physicochemical processes during biotransformation of the wastes indicates the maturity of the compost. As a result, the compost becomes enable to nurture the plants and increase humus to the soils [24].

Measurement of pH, electrical conductivity, total dissolved solids, salinity

To measure the pH of the waste and compost, 5 ± 0.1 g of sample was included in 100 mL freshly deionized water and shaken for 16 to 24 h. Then, the filtrate pH was measured by a pH meter (BT-675, BOECO, Germany). A conductivity meter (CT-676, BOECO, Germany) was utilized for electrical conductivity and salinity determination. The total dissolved solids (TDS) was measured with the same device and by APHA-2540 D method.

Moisture content

The Loss on Drying (LOD) method was applied to determine the moisture. About 5 g sample was dried at 105°C in an oven for 24 h, cooled and weighed. The process was repeated until a constant mass was gained. The moisture was calculated from the equation (i).

$$\text{Percenatge of moisture} = \frac{T_1 - T_2}{T_1} \times 100 \ldots\text{(i)}$$

Here, T_1 is the mass of the sample before drying and T_2 is the mass of the sample after drying.

Solids content and heavy metal determination

EPA 1684 method [25] was followed for total solids (TS), fixed solids (FS) and volatile solids (VS) determination of final compost. About 25 ± 0.1 g compost sample was dried at 103ºC to 105ºC for 12 h. The residue after drying was air-cooled weighed and again burnt at 550ºC for 2 h. The mass difference of the sample before drying and after drying was used for calculating TS, VS and FS. For heavy metal determination in the final compost, an evenly mixed compost sample was digested in acid as per the EPA 3050B method [26]. Heavy metals in the aliquot were quantified by atomic absorption spectroscopy (Spectra240FS AA, Agilent, USA). Each data was measured in a set of three.

NPKS determination

To determine total nitrogen (TN), standard procedure of micro-Kjeldahl method by AOAC [27] was followed. The compost was air-dried in the shade, powdered with pulverizer (Pulverisette 14, Fritsch GmbH, Germany) through 2 mm mesh size sieving and stored for chemical assay. The phosphorus (P) was estimated by the spectrophotometric molybdovanadate method. The available potassium (K) was determined by extracting it from the compost with neutral normal ammonium acetate solution. The estimation of K was carried out by flame photometer. The turbidimetric method was followed for sulphur (S) determination.

Scanning electron microscope (SEM)

The SEM image of the initial liming sludge mixture and final compost were obtained after degradation and maturity of the final compost was achieved. For this purpose, SEM (JEOL JSM-6490, USA) was utilized. The micrographs of dried, ground compost powders were obtained at 250X magnification with an accelerating voltage of 15 kV.

Maturity and phytotoxicity assessment

Direct phytotoxicity of the compost was analyzed to ensure its maturity. Ten seeds of ladies finger (*Abelmoschus esculentus)* was put in the crocks containing compost organic fertilizers and were incubated for 7 days in a darkened environment. Sufficient water was sprinkle was during the incubated period.

Results And Discussion

Characteristic of compost materials

The pHs of the composting materials (LS, CD, CM and SD) were between the ranges of 7.37 to 8.54 and the moisture ranged from 39.16 to 42.52% (Table 1).

Table 1. Characteristics of compost ingredients

Materials	Dry matter (%)	Moisture (%)	pH
Liming sludge	60.84±0.30	39.16± 0.30	8.51± 0.53
Cow dung	55.66±0.41	44.34± 0.41	7.23± 0.61
Chicken Manure	60.26±0.65	39.74± 0.65	7.37± 0.74
Sawdust	57.48±0.67	42.52± 0.67	7.51± 0.47

It is well known that a wide pH range is responsible for the composting process. Hung et al. [28] reported that typically the optimal pH range 6.5 to 8.5 is favoured for composting, but if the range is higher, this pH range will result in ammonia volatilization and odour problems. Table 2 shows the physicochemical properties of the mixed compost materials for three different piles. The pH of the compost mixture was within 7.8 to 8.2, which is optimum for the composting process.

Table 2. Physicochemical parameters of raw liming sludge mixture

Parameters	P#1	P#2	P#3	Unit
pH	7.9±0.3	7.8±0.4	8.2±0.2	-
TDS	5.12±0.3	3.8±0.4	5.51±0.5	g/L
Salinity	5.9±0.2	4.2±0.3	6.3±0.3	Ppt
Conductivity	12.09±0.1	8.81±0.2	11.62±0.3	mS

Characteristics of compost

Table 3 shows the physicochemical properties e.g., pH, total dissolved solids (TDS), salinity, conductivity, moisture (%), dry matter (%), fixed solids (%), volatile solids (%) and electrical conductivity (EC) of the final compost. The pH of the compost was found within 7.4 to 7.6 which had decreased over time. During composting, initially, pH becomes low due to organic acid formation which indicates the progress of the composting process; towards the end, the pH becomes neutral. The generated organic acids are then transformed into methane and carbon dioxide. After maturation of compost, pH of compost piles P#1, P#2 and P#3 were 7.6, 7.4 and 7.6, respectively. On the other hand, TDS, salinity and conductivity had increased which indicates that the organic materials had been broken down into smaller parts.

Table 3. Physicochemical parameters of the final compost

Parameters	P#1	P#2	P#3	Unit
pH	7.6±0.4	7.4±0.2	7.6±0.3	-
TDS	7.16±0.2	7.42±0.3	7.31±0.1	g/L
Salinity	8.5±0.1	8.7±0.2	7.4±0.1	Ppt
Conductivity	16.72±0.3	17.62±0.4	13.02±0.2	mS
Moisture	39.15±0.25	41.81±0.29	43.83±0.36	%
Dry matter	60.83±0.25	58.19±0.29	56.19±0.36	%
Fixed solids	49.61±0.79	55.30±1.39	50.07±0.79	%
Volatile solids	50.39±0.79	44.70±1.39	49.93±0.788	%

It is clear from Table 3 the highest amount of dry matter (60.83%) was in the compost pile P#1 that fulfils both the standards of Switzerland and Great Britain [29]. The dry matter in the piles P#2 and P#3 was nearly the same amount, which was 58.19% and 56.19%, respectively. These values have fulfilled the standard of Switzerland and Great Britain but are significantly below the standard of India [29]. The volatile solids content in composts P#1, P#2 and P#3 were 50.39%, 44.70% and 49.93%, respectively. The loss of volatile solids in the compost is the result of microbial decay of organic matter of the compost ingredients.

Monitoring of compost pile temperature

Temperature changes in compost piles P#1, P#2 and P#3 during composting is shown in Fig. 2. The figures illustrate that in each pile there was a drastic change in temperature after a time interval. The highest temperature found in P#1, P#2 and P#3 were 59.69°C, 64.41°C and 63.36°C on the 11th, 12th and 18th day of composting, respectively.

Till the 56th day of composting, the temperature varied from 40°C to the highest temperature found for each pile. At this temperature range, thermophilic bacteria accelerate the breakdown of proteins, fats, and complex carbohydrates. Also, the high temperature ensures the destruction of pathogenic microorganisms. The compost piles were frequently revolved when the temperature was around 40°C.

Revolving is an important factor during composting because air circulation causes rapid growth of microorganisms as well as expansion of microorganism activities whereas the shortage of oxygen supports the growth of anaerobic microorganism resulting in an unpleasant odor [29].

After revolving, the temperature rises again to continue the thermophilic phase. The temperature in the range from 55 to 65°C allows for considerable destruction of pathogenic organism [30].~~30~~ Therefore, the compost piles were revolved when the temperature became stable or below the thermophilic range (<40°C). It is noticeable in the figures that there are peaks and troughs which are the result of frequent (weekly) revolving of compost pile during the composting process. In this study, compost piles (P#1, P#2 and P#3) show the normal temperature change patterns. Usually temperature changes during composting are used as the feedback parameter of the process. In this case, there were no remarkable temperature differences among the compost piles. Up to the 56th day, the temperature was above 40°C; afterwards, it gradually decreased although the compost piles were revolved which indicates the degradation of the solid wastes was completed.

Monitoring of day temperature

During composting, the day temperature was monitored for the period of composting. Fig. 3 depicts the day temperature during the composting. This study was conducted at the end of August; therefore, from the beginning of composting, the temperature gradually decreased.

On the first day of composting (1st day), the temperature was 33.03°C and then gradually it was increased to 34.49°C. The highest and the lowest day temperature during the composting period was 34.49°C (2nd day) and 21.42°C (61th day), respectively. When compared, results show that the day temperature change does not affect the compost pile temperature. It is clear that at the end of composting, the pile temperature was close to the day temperature e.g., on the 80th day, it was 24.35°C and the temperatures of P#1, P#2, and P#3 were 25.71°C, 28.93°C and 29.96°C, respectively.

Quality of compost

NPKS content in compost

Table 4 shows the compost nutrients in terms of N, P, K, and S for each compost pile. The Total Kjeldahl Nitrogen (TKN) in compost piles P#1, P#2 and P#3 were 0.8%, 0.6%, and 1.1%, respectively. The amount of TKN content in the compost also fulfilled both standards of India and Great Britain [29]. Only TKN content in compost pile P#3 fulfilled the standard of Switzerland. However, the K content of all the compost piles was 0.6% which fulfilled the Great Britain standard but was below the Indian standard. The P values of the compost were within the standard range of India. The S content in the compost was within the Bangladeshi standard but there is no standard value for Switzerland or India or Great Britain. However, the nutrient of compost was enough for the soil conditioner.

Table 4. Quality of final liming sludge compost

Parameters	**P#1**	**P#2**	**P#3**	**Unit**
Nitrogen (N)	0.8±0.1	0.6±0.03	1.1±0.3	%
Phosphorus (P)	0.7±0.13	0.5±0.01	0.8±0.15	%
Potassium (K)	0.6±0.11	0.6±0.02	0.6±0.07	%
Sulphur (S)	0.4±0.02	0.5±0.1	0.5±0.05	%
Cr	18.15± 5.3	21.02± 4.3	19.7± 3.8	mg/kg
Pb	ND	3.30±0.5	1.84±0.2	mg/kg
Cu	21.20±2.7	19.01±3.01	20.68±1.7	mg/kg
Zn	152.64±3.8	128.78±4.9	148.22±7.04	mg/kg
Ni	6.22±1.5	5.40±1.4	6.93±2.01	mg/kg
Cd	3.96±2.1	5.78±0.9	4.83±1.1	mg/kg

Metal content in compost

Table 4 shows the metal element of the final compost. The amount of metals content e.g., Cr, Pb, Cu, Zn, Ni, and Cd were lower in the three piles for utilization in agricultural activities [29].~~29~~ The highest and lowest amount of Zn in the compost pile P#1 and P#2 was 152.64 and 128.78 mg/kg which is significantly below for inland land tracts. However, it is seen that all metal values in the compost piles satisfy the requirements for use in agricultural land, with no risk of soil or plant contamination.

Phytotoxicity of Compost

Seven (7) days after sowing, ladies finger (*A. esculentus*) seed germination was observed. The germination found for the three compost is shown in Fig. 4. In crock1, germination was observed after 7 days where the seeds begin to germinate. In crock 2 and crock 3, the germination was observed for 10 days and 12 days, respectively. It is clear that after 10 as well as 12 days the seeds were germinated with two leaves.

The maturity of compost dictates the completion of degradation of the compost mixture and the completion of the process [31]. The stability of the prepared compost was ensured by the consistent temperature of the compost and freeing of odour from decomposition. This indicates sufficient microbial biomass activity [32] which is necessary for nutrient transfer. It reveals the existing condition of phytotoxic organic acids in the compost. The heavy metal and NPKS analysis showed the numeric value of the nutrient and the seed germination test which assures the maturity, stability and phytotoxic level of the compost. The growth of the seedling satisfies the inquiry about the applicability of the compost on an industrial scale.

SEM analysis

The morphological study of the liming sludge mixed with matrix and final compost were examined through SEM. Fig. 5 depicts the SEM of primary raw liming sludge mixture with matrix and the final compost.

The left panel depicts (P#1a, P#2a, P#3a) the liming sludge mixed with matrix and right panel indicates (P#1b, P#2b, P#3b) the final compost. The SEM images of the initial raw mixture sample shows the aggregate of biomass where the matrix is firmly bonded. This is consistent with the study conducted by Ravindran and Sekaran [22]. The final compost manure expresses progressive degradation by microbial organisms. This indicates that the microorganism i. e., bacteria have attacked the composting materials and degraded and separated the particles. The images provide visual assurance about the stability and maturity of the compost into humus-rich organic components. Similar images were also found during bacterial composting carried out by Zhang et al. [33] Ravindran and Sekaran [22]. This leads to the conclusion that the microbes attacked non-fibrillar proteins and denatured these during composting.

Implications of the study

Bangladesh produces around 2.55×10^6–3.4×10^6 m^3 wastewater every year from 85000 tons of raw hide/skin processing[5,8] to convert into leather. During leather processing, basic chromium sulfate ($Cr(OH)(SO_4)$) is utilized worldwide [34, 35]. Before discharging the wastewater, inorganic coagulants are applied to precipitate the settleable solids known as tannery sludge [36, 37]. This sludge contains heavy metals (especially chromium), organic compound, as well as pathogenic micro-organisms [38]. The toxic heavy metals in tannery sludge render a challenge to apply the sludge as a fertilizer [39], land filler [40] or soil amendment material [41]. However, application of these disposal methods causes the plants to take up the heavy metals, disturb agricultural output, poses potential ecological threats, and promotes secondary pollution [42, 43].

About 60-70% of the tannery sludge is generated from hair dissolving liming operation[7] where the wastewater stream contains keratin, non-structural protein e.g., albumins, globulins, etc. along subcutaneous adipose tissue but no heavy metals. The sludge generated from liming operation only is enriched with carbonaceous materials which pose no above mentioned threat during application. This study will not only decrease the sludge load but also establish a hazard less pre-treatment free application method. This will also lessen the sludge load in CETP and produce an environmentally sound value added product.

Conclusion

This study is a testament to inventiveness towards sustainable management of hair burning liming sludge in tannery without any preliminary treatment or conditioning through bacterial composting. The results show that the pH, heavy metal and other nutrients of the compost were within the required beneficial level for the soil and plants. The comparison of day temperature with the precipitous change in the composting pile temperature indicates the destruction of pathogenic microorganism and rapid degradation of the waste. Moreover, SEM analysis supports the degradation of the composting materials and germination test speaks to the applicability of the compost in agriculture purposes. Tannery authority could design the treatment of liming wastewater sludge through compost processing to reduce the pollution load and produced compost can be used as organic fertilizers.

Declarations

Ethical Approval

The authors declare that the submitted manuscript is original. Authors also acknowledge that the current research has been conducted ethically and the final shape of the research has been agreed by all authors. Authors declared that this manuscript does not involve researching about humans or animals.

Consent to Participate

The authors consent to participate in this research study.

Consent to Publish

The authors consent to publish the current research in Applied Biochemistry and Biotechnology Journal.

Authors Contributions

Md. Abul Hashem: visualization/conceptualization, investigation, methodology, writing-review, editing, and supervision. Md. Sahariar Sahen: investigation, methodology, data managing-organizing, writing-original draft, and writing-review. Mehedi Hasan: sampling, data collection, reviewing. Sofia Payel: review and editing. All authors read and approved the final manuscript.

Funding

This work was supported by the Advanced Studies & Research (CASR), Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh

Competing Interests

The authors declare no conflict of interest.

Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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Figures

Figure 1

Composting piles: P#1, P#2, and P#3 with aerobic window.

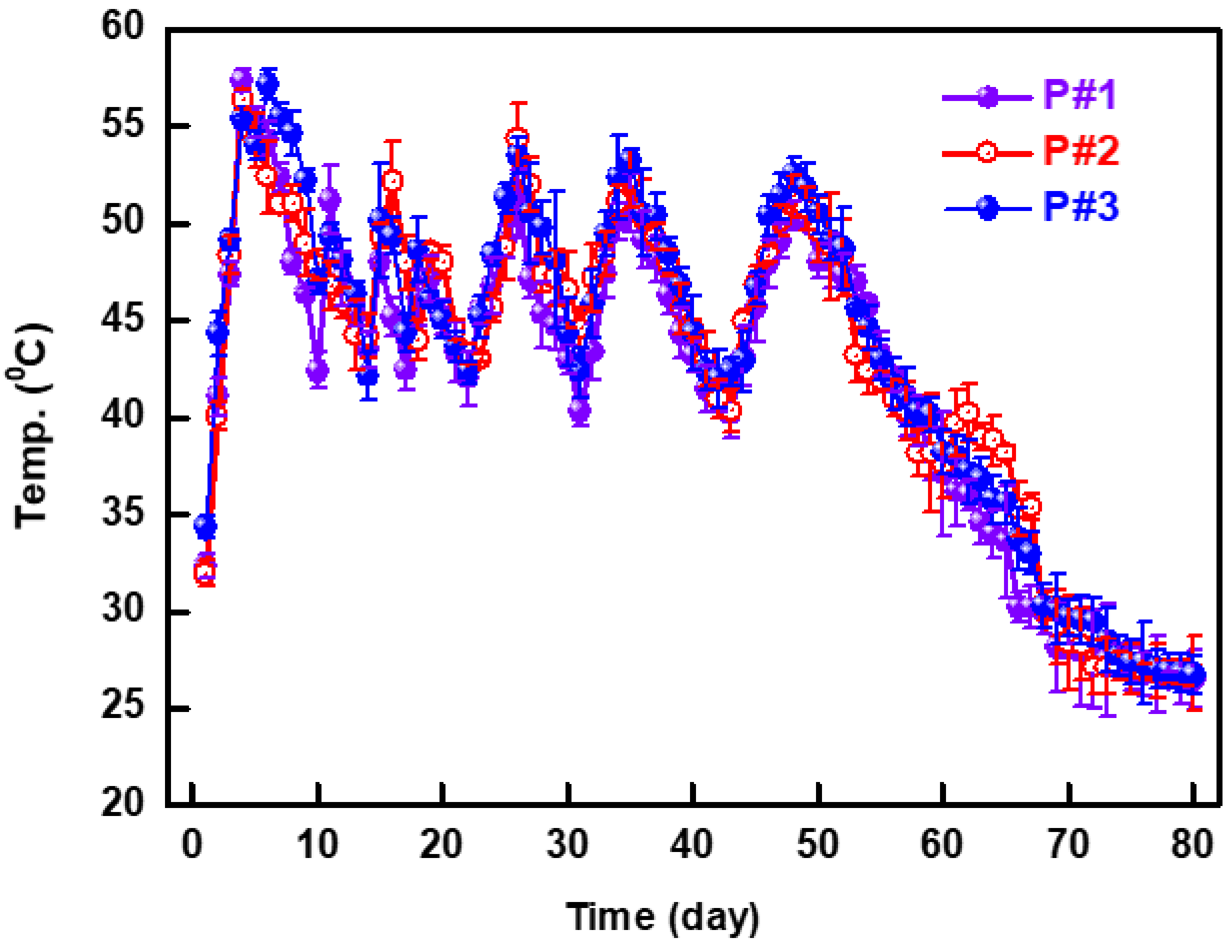

Figure 2

Temperature changes in compost processing P#1, P#2, and P#3

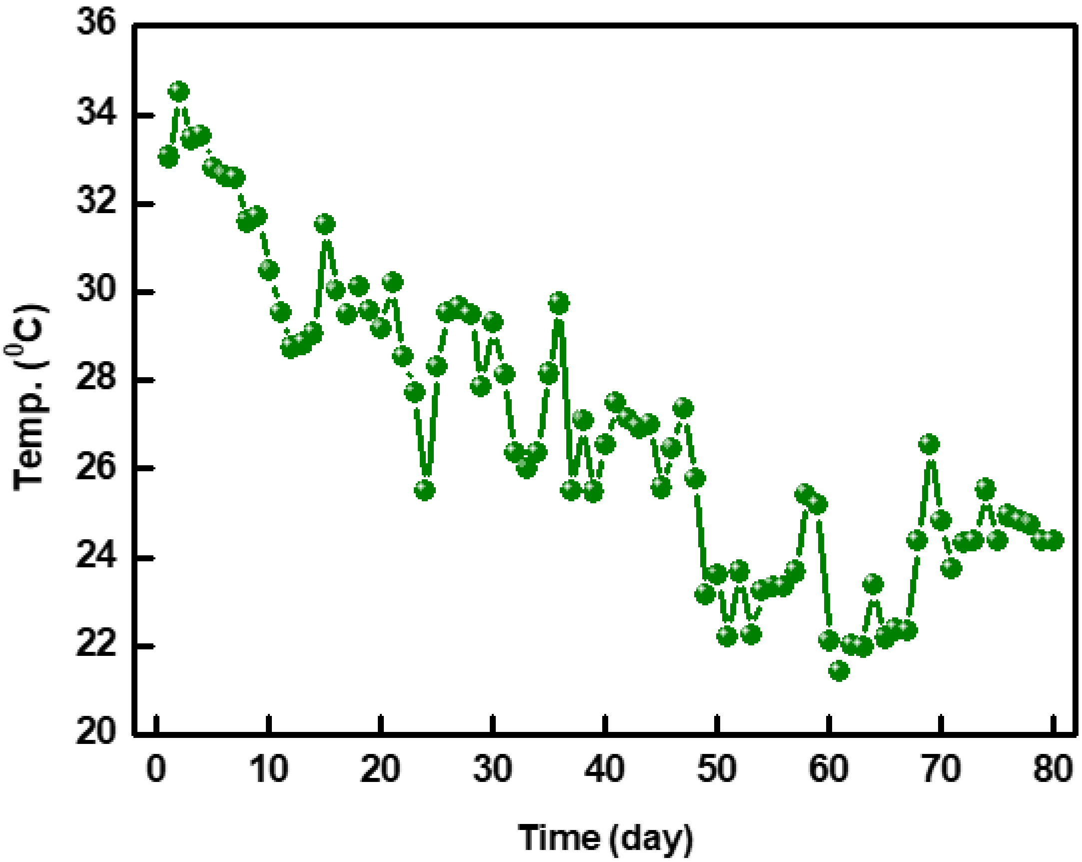

Figure 3

Monitoring of day temperature during composting

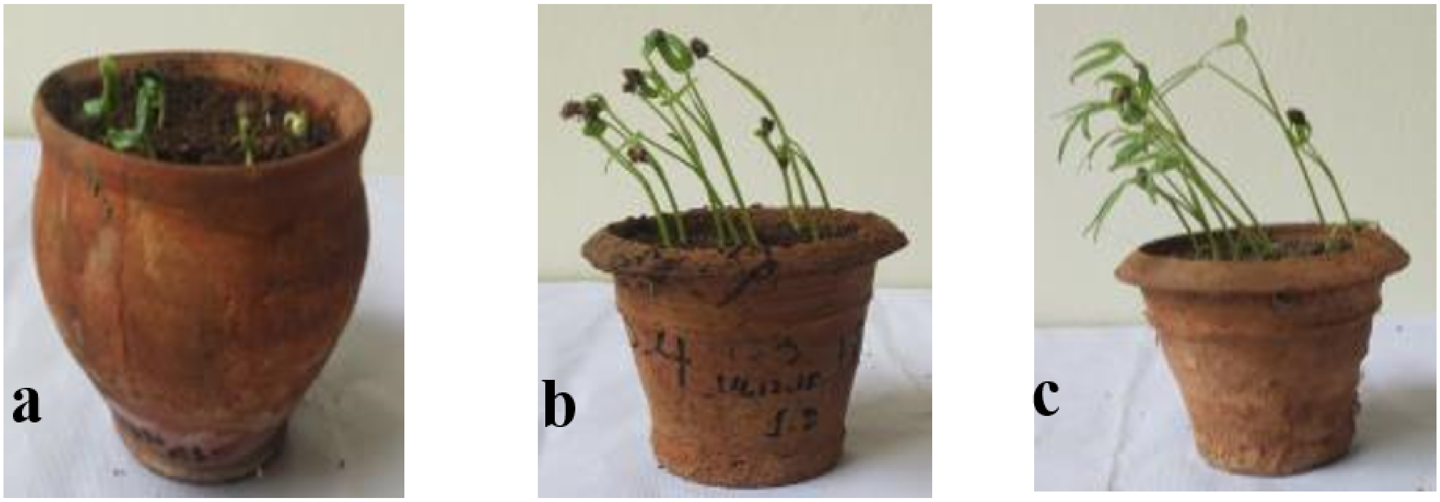

Figure 4

Germination of the A. esculentus seeds a) after 7 days b) after 10 days and c) after 12 days

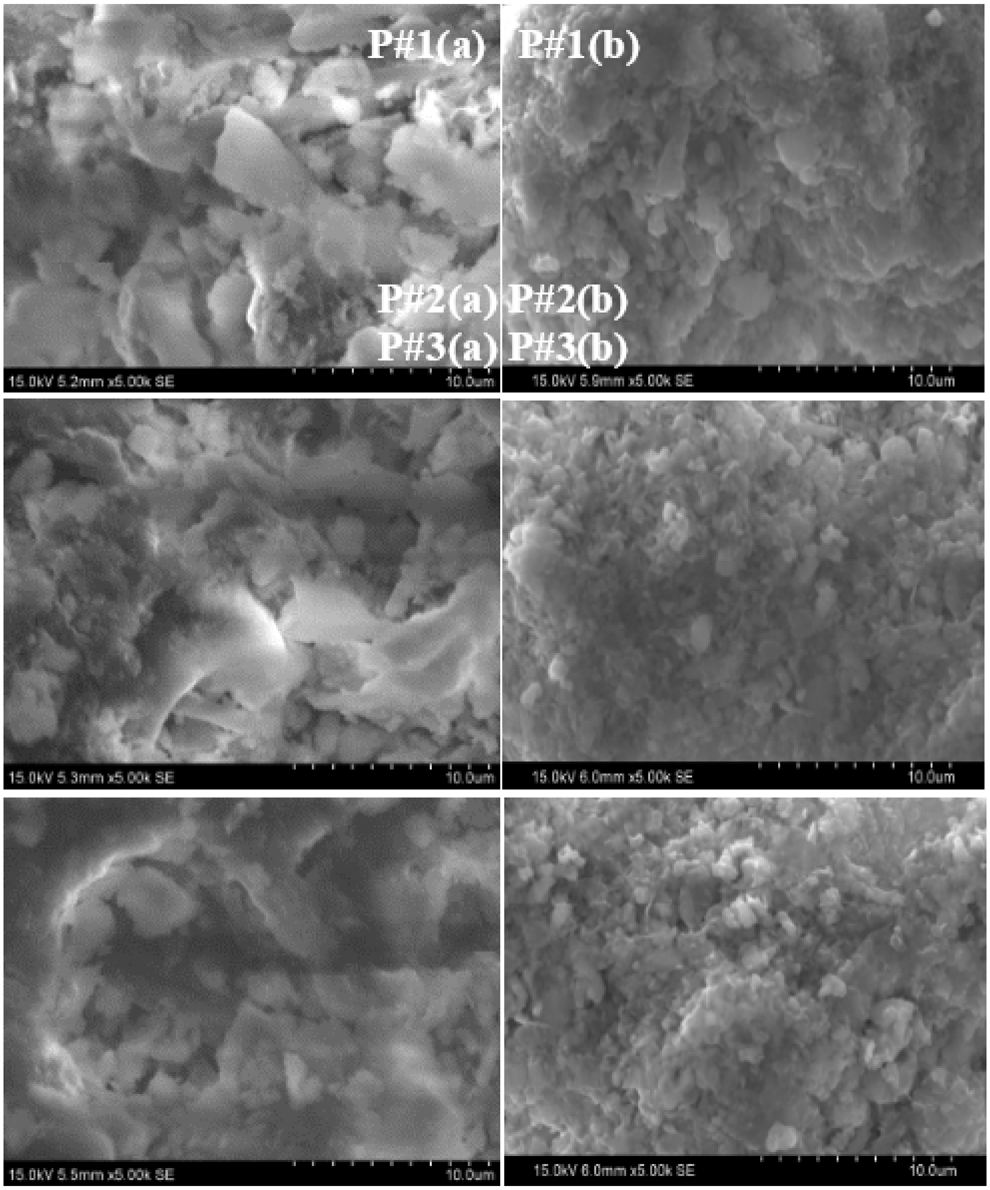

Figure 5

SEM images: (P#1a, P#2a, P#3a) raw liming sludge with matrix mixture, and (P#1b, P#2b, P#3b) final compost