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Evaluation of the bio-drying process of municipal solid waste using rotating drums Bio-drying rotary drum

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Abstract: Most of the municipal solid waste collected is disposed of in landfills and controlled landfills. However, efficient ways of recovering these wastes have emerged, such as bio-drying. This technique uses the exothermic degradation reaction of organic matter carried out by microorganisms along with aeration to reduce the moisture of the waste. The objective of the research was to test the bio-drying technique in a rotary drum. For this purpose, three rotary drums were built, and the tested residue was synthetically produced. The aeration rate tested was 1 liter per kilogram per minute, and rotation was performed for one minute every three hours. The analyses performed on the residues were moisture content, volatile solids, calorific value, particle size, and temperature profile. The residues entered the bio-drying process with a moisture content of 52%, 49%, and 54% and went out with 15%, 13%, and 10% for drum 1, 2, and 3, respectively, a reduction of more than 70%. The calorific value increased by 95%, 88%, and 122% for drum 1, 2, and 3, respectively. During the process, no leachate generation was observed.

Key words: Bio-drying, municipal solid waste, moisture, rotating drum.

INTRODUCTION

Population growth, together with current society's consumption habits, economic development, degree of industrialization, and regional climate (Hoornweg & Bhada-Tata 2012, Martínez et al. 2013) are the leading causes of the increase in waste generation. Global municipal solid waste (MSW) generation levels are around 1.3 billion tonnes per year, with an estimated increase to 2.2 billion tonnes per year by 2025, representing a significant increase in per capita generation from 1.2 to 1.42 kg per day (Hoornweg & Bhada-Tata 2012). In Brazil, MSW production in 2018 was almost 79 million tons, an increase slightly below 1% compared to 2017 (ABRELPE 2019).

Given the large waste production, both worldwide and nationally, Mendes (2014) stressed that there is a significant concern regarding the proper disposal, that is, that this resource is appropriately valued for reducing the pressure on the environment. MSW management might include source reduction, reuse, separation and recycling, combustion with or without energy recovery, and ultimately landfill disposal (Ouda & Raza 2014). In Brazil, NSWP (National Solid Waste Policy) (Brazil 2010) brings an order of priority in waste logistics and management, namely, non-generation, followed by reduction, reuse, recycling, treatment, and environmentally appropriate final disposal.

However, the landfill method is widely used for the disposal of municipal solid waste, especially in developing countries (Yang et al. 2018). In Brazil, 72.7 million tons of waste were collected in 2018, from which 59.5% (43.3 million) was disposed of in landfills and the remainder (40.5%) was disposed of in inappropriate places, such as dumps or controlled landfills, which do not have a set of systems to mitigate the environmental impact (ABRELPE 2019).

Currently, there are more efficient ways to treat MSW, especially those that use waste for energy recovery, known as “Waste to Energy” (WtE). According to Ouda & Raza (2014) WtE is a proven and efficient option to address the challenges of MSW disposal, with the advantage that it can meet part of the growing global energy demand.

An example of WtE technology is bio-drying. This technique is an option for the bioconversion reactor used in a biological-mechanical treatment plant and is even considered an alternative for the treatment of MSW (Velis et al. 2009, Rada et al. 2006). The bio-drying process can be applied to MSW both for energy use and for pre-treatment and subsequent landfill, as there is a reduction in volume and leachate.

Biodrying reactors use a combination of modified physical and biochemical processes. In the biochemical process, aerobic biodegradation of easily degradable organic matter occurs. In the physical aspect, moisture removal by convection is achieved through controlled aeration (Velis et al. 2009). Among the many advantages of bio-drying, there is thermal heat generation due to microbial action, whereas in traditional drying processes, external heat sources are needed (Rada et al. 2007, 2010).

The reactor design includes a container along with an aeration system. Biodrying reactors can be either closed or open (static) containers or rotating (dynamic) drums; however, most commercial bio-drying projects use static reactors (Velis et al. 2009). Among the static reactors, it is possible to find different project designs (Adani et al. 2002, Rada et al. 2006, Colomer-Mendoza et al. 2013, Santosa et al. 2015, Tom et al. 2016). On the other hand, the literature found on rotating drums is still little diversified (Skourides et al. 2006, Bartha & Brummack 2007, Bartha 2008, Rodríguez et al. 2012, Somsai et al. 2015, Patcharavongsiri et al. 2016).

Although the most commonly used reactors are the static ones, their project presents a few problems, such as heterogeneity in waste drying and, consequently, interference in the calorific value (Tom et al. 2016, Velis et al. 2009). This problem can be solved by the use of (1) rotary percussion reactors (Skourides et al. 2006, Bartha & Brummack 2007, Bartha 2008) and (2) inverted airflow designs (Sugni et al. 2005).

For the bio-drying process, some factors are crucial, such as waste moisture, the temperature reached during the process, the applied aeration rate, and the calorific value.

MSW has a high concentration of food and organic waste; therefore, it contains a high moisture content (Ab Jalil et al. 2015). The decline in moisture content after the bio-drying process enables heat treatment, such as incineration, as well as mechanical separation for beneficial use (Zhang et al. 2009, 2011, Colomer-Mendoza et al. 2012, Ab Jalil et al. 2015).

The water content of the waste matrix is the single most crucial variable for evaluating bio-drying process performance. Two main steps reduce the moisture content in the waste matrix: i) the water molecules evaporate from the surface of the waste fragments into the surrounding air, and ii) the evaporated water is conveyed through the matrix by the airflow and removed with the exhaust gases. An amount of free water can seep into the waste matrix and be collected at the bottom of the reactor as leachate (Velis et al. 2009).

Another critical factor in the bio-drying process is the temperature increase, which depends exclusively on exothermic reactions carried out by microorganisms that degrade easily degradable organic matter (Martínez et al. 2013). Regarding the bio-drying process' general behavior, Zhao et al. (2010) observed a pattern similar to composting. The temperature profiles showed three stages: a thermophilic stage (45 and 55 °C), a moderate temperature stage (40 and 45 °C), and a cooling stage (below 30 °C) (Kristanto & Zikrina 2017, Tambone et al. 2011). High temperatures cause the elimination of the septic nature (elimination of pathogens) and keep the residues free from odors for much longer (Tom et al. 2016).

In bio-drying processes that use rotary drums, one of the factors that affect temperature is the rotary movement of the biomass, carried out to ensure the homogeneity of moisture content and, thus, of the calorific value. This procedure causes the matrix temperature to fall, subsequently rising again, although the peak value and the increasing rate are lower than before the turning point (Zhao et al. 2010).

Aeration is an operational parameter in bio-drying, being one of the main factors affecting the process performance and should be adequately controlled for a successful bio-drying (Sadaka et al. 2011, Zhang et al. 2015, Ab Jalil et al. 2015). Aeration provides a mass and energy flow, allowing the removal of water content; heat transfer redistribution, removing excessive heat and adjusting the matrix temperature; oxygen supply to meet the stoichiometric demand for aerobic decomposition (Velis et al. 2009, Navaee-Ardeh et al. 2010, Zhang et al. 2015).

Airflow rates act as a means of heat transport that spread throughout the environment, exerting a remarkable influence on the temperature increase during the process. The airflow rate may affect the drying process, indicated by the heat generated during the process due to dehydration (Kristanto & Hanany 2017). Low aeration rates result in decomposition without significant moisture removal, in other words, composting (Sadaka et al. 2011) and may also favor leachate formation (Colomer-Mendoza et al. 2013). Higher aeration rate values rapidly cool the material (Navaee-Ardeh et al. 2010) and disrupt microbiological activity (Sadaka et al. 2011).

The net heating value (NHV) is a more significant indicator for combustion than the higher heating value (HHV), since NHV reflects the heating value of the wet material, considering the evaporation of water during combustion, while HHV indicates only the amount of heat generated by the complete combustion of the dry material (Zhang et al. 2009b).

Given the above, a rotary drum was built to test the bio-drying technique using synthetic municipal solid waste.

MATERIALS AND METHODS

Construction of rotary drums

Due to the heterogeneity of the output material in static reactors, it was decided to build rotating drums. The equipment basically consisted of three drums in parallel, all with the same configuration. For the construction of the rotary drums, three 200-liter metal drums were used. A fixed shaft was added to each drum and bearings, retainers, and pulleys were attached to it. The pulleys' connection was made with belts; an engine and a reduction were responsible for the rotation of the drums. The electrical system had a digital timer to adjust the interval between revolutions. The system aeration was elaborated through a compressor, pressure regulators, and flow meters to control the system input airflow. Air inlet and outlet were added to the axis itself, entry at the bottom of the drum, and exit at the top. The aeration system also relied on the exhaust of the drum's internal air, thus forcing the exit, aiming at the non-condensation of water particles inside the reactor. Temperature variable monitoring was carried out through sensors installed internally and externally to the drums. Fins were added to optimize waste homogenization. The drum set had thermal insulation made with cork (Figure 1).

Synthetic municipal solid waste (SMSW)

The gravimetry used for the bio-drying process was calculated for a total of 60% of organic matter, based on the average of the study carried out by Tavares (2007) for the Metropolitan Region of Curitiba-Brazil (Table I). However, following what was proposed by Ragazzi et al. (2011) the solid urban waste necessary for the experiments was artificially produced, avoiding hygiene and safety problems and ensuring representative corrections related to the selected scenarios.

SMSW was made up of organic matter, paper, cardboard, plastic film, rigid plastic, rubber, wood, rags, and leather. All elements that were part of the SMSW were obtained and crushed separately, being subsequently mixed according to their corresponding fraction for a total of 5 kg. Figure 2 shows the synthetic municipal solid waste that was sent to the bio-drying process.

SMSW analysis

Moisture content is a variable of extreme interest for the bio-drying process, so it was monitored daily by oven drying the material with air circulation at 40 °C for 48 hours.

The tests to determine the volatile solids (VS) content of the samples were performed as proposed by Zhang et al. (2011) and Shao et al. (2010), i.e., keeping the sample at 550 °C for 6 hours. VS analyses were performed in triplicate and only on the bio-drying rotary drum's input and output residues.

It was necessary to know the higher heating value (HHV) and lower heating value (LHV) of SMSW to obtain the samples' NHV. Thus, the SMSW sample was prepared, and HHV was found using ASTM D-240-17 (Standard Test Method for Heat Pump Liquid Fuel Hydrocarbon Combustion Heat) (ASTM 2017); analysis performed at the Biomass Laboratory of the Federal University of Paraná (UFPR). While for LHV, it was necessary to find the hydrogen content present in the SMSW sample through the elementary analysis of the SMSW, which was performed at the Analytical Center of the University of São Paulo. From the HHV, LHV, and moisture content of the SMSW, the bio-drying process input and output NHV was calculated using the equation proposed by Brito & Barrichelo (1982):

$$NHV = LHV * [(100 - w) / 100] – 6 * w$$

Where:
NHV: Net heating value ($kcal \cdot kg^{-1}$)
LHV: Lower heating value ($kcal \cdot kg^{-1}$)
W: Moisture content (%)

For the granulometry test, sieves of 50.8 mm, 38.1 mm, 25.4 mm, and 12.7 mm openings were used, i.e., the sample was subdivided into five parts, and the sample retained in each sieve was weighed (Shao et al. 2010).

Bio-drying process operational variables

The bio-drying run was performed at an aeration rate of 1 L kg^{-1} min^{-1} with an interval between rotations of 3 hours. The speed set for the rotation was 9 rpm.

RESULTS AND DISCUSSIONS

Temperature and volatiles solids

The temperature of the waste mass varied between 15 and 30 °C, following the drums' external temperature variation (Figure 3). Due to the degradation of organic matter, the temperature of the waste mass should have increased, as it is a reaction that releases heat; however, this fact was not observed. Some

Figure 1. **Overview of rotating drums.**

reasons may have led to this, such as the high aeration rate (Zhao et al. 2010) and the low amount of volatile solids present in the waste mass (Rada et al. 2005), which may have influenced the bio-drying process as a whole. No cooling of the mass of waste from turning has been recorded.

The VS reduction is an essential parameter in bio-drying, as microbiological activity reduces the volatile solids content in the waste; however, a significant drop is not desired (Kristanto & Zikrina 2017), since it decreases the calorific value.

There was no trend towards a reduction in the volatile solids content, which is in agreement with the temperature variable, that is, the temperature did not increase due to the low or non-existent microbiological activity; consequently, there was no consumption of volatile solids. The variation found in VS values may be attributed to the high heterogeneity of the material (Figure 4).

Moisture content of the SMSW

The purpose of bio-drying is to reduce the moisture in municipal solid waste, so the moisture content is one of the most vital response variables. The SMSW used herein had a 60% fraction of organic matter, resulting in an input SMSW moisture content of 52%, 49%, and 54% for drum 1, 2, and 3, respectively (Figure 5).

Table I. **Materials used for the constitution of synthetic municipal solid waste and respective percentage of mass.**

Material	Percentage of mass (%)
Organic Matter (beet, carrot, cabbage and lettuce, 25% of each element)	60
Paper	12
Cardboar	3.8
Film Plastic	11.8
Rigid Plastic	5.2
Rubber	0.8
Wood	0.5
Rags	4.7
Leather	1.1
Overall	100

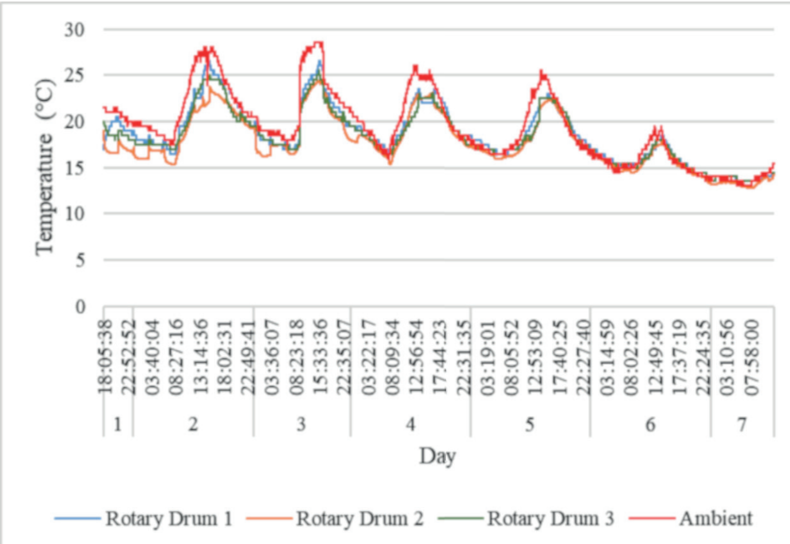

Figure 2. Synthetic municipal solid waste sent to the biodrying process.

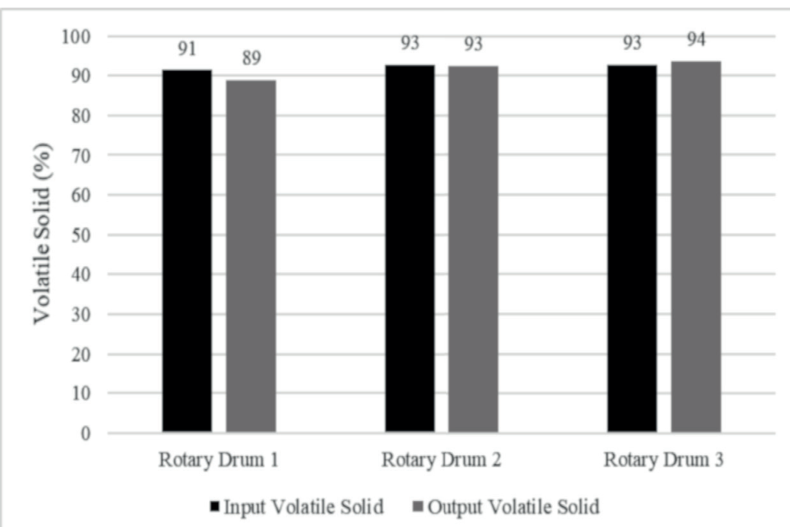

Figure 3. Temperature profile during bio-drying.

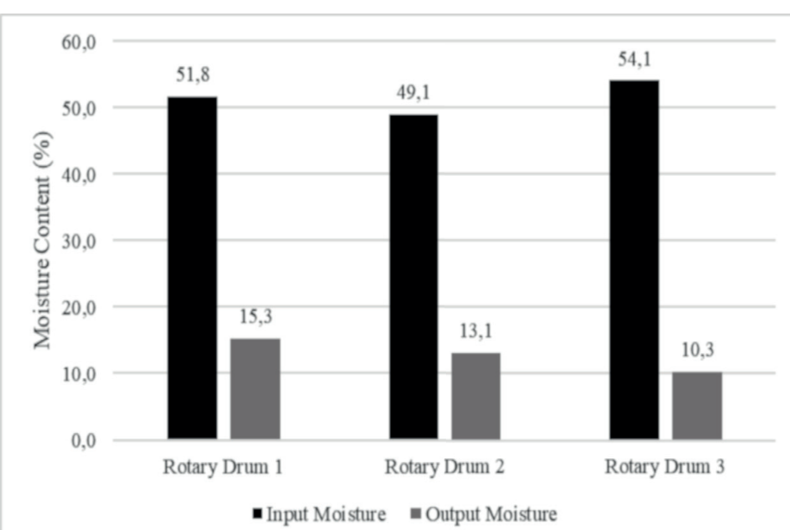

Figure 4. Volatile solids content of SMSW.

Low moisture content may limit the decomposition rate (Adani et al. 2002) as it slows down microbiological activity (Grilli et al. 2012). Generally, moisture content below 35% based on wet mass will be biologically inactive (Gómez et al. 2006, Colomer-Mendoza et al. 2012). When moisture content levels are too low, microbial activity decreases because water is required for microbial metabolic processes. If the moisture content is above 65%, anaerobic conditions are more frequent because water instead of air fills the pore space, limiting the available oxygen (Sadaka et al. 2011). Therefore, the moisture content of the incoming SMSW was not close to the critical values, i.e., below 35% and above 65%.

After six days of bio-drying, the moisture content of the RSUS was 15%, 13%, and 10%, which means a 71%, 73%, and 81% reduction in the SMSW's moisture content of drums 1, 2, and 3, respectively.

Shao et al. (2010) performed bio-drying with an initial moisture content of 73%, reducing it to 48.3% after the process. Martínez et al. (2013) used raw material with a moisture content of 64% and, after the bio-drying process, this value decreased by 91%. Tom et al. (2016) researched waste whose moisture content dropped from an initial 61.25% to 48.5% after 33 days, representing a 20.81% reduction. Kristanto & Zikrina's (2017) experiments showed a reduction in the moisture content of 16.03%, 24.41%, and 37.3%. Kristanto & Hanany (2017) obtained materials with a moisture content of 36.32%, 21.15%, and 21.02% at the end of the bio-drying process.

During bio-drying, leachate production and moisture gradient in the waste mass were not verified. Sugni et al. (2005) and Tom et al. (2016) observed the heterogeneity in the distribution of moisture within the reactor matrix, because of evaporated water condensation at the top of its matrix. The air carried the moisture from the bottom and reached the saturation point when passing through the matrix. Thus, when reaching the top of the column, the air could not absorb more water. Adani et al. (2002) and Zhao et al. (2010) eliminated the moisture gradient and made the materials more homogeneous by the waste mass turning.

As there was no increase in temperature, the SMSW mass may have reduced the moisture

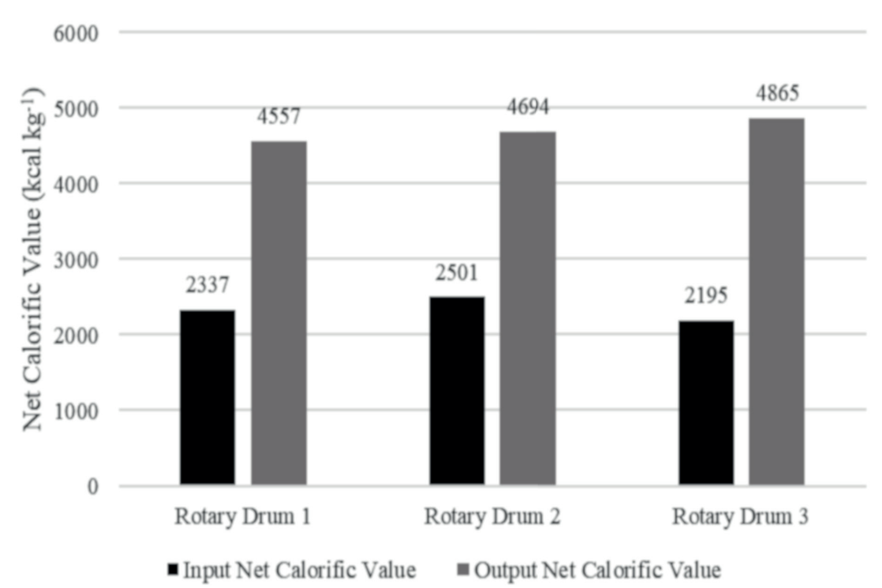

Figure 5. **Moisture content of SMSW.**

content due to convective evaporation (Velis et al. 2009).

Net heating value

The net heating value is closely linked and is inversely proportional to the moisture content, the lower the moisture content of the waste, the higher the net heating value (NHV) (Colomer-Mendoza et al. 2013). Adani et al. (2002) reported that, unlike HHV and LHV, NHV is affected by the sample's water content. Water losses cause an increase in the total solids (TS) content, increasing PCU.

The SMSW input into the process showed a low NHV as the waste had a high moisture content. The NHV of drums 1, 2, and 3 were 2337, 2501, and 2195 kcal kg^{-1}, respectively (Figure 6). As a high moisture content was removed through bio-drying, the NHV values reached 4557, 4694, and 4865 kcal kg^{-1} after the process, denoting an increase of 95%, 88%, and 122% for drums 1, 2, and 3, respectively.

Tambone et al. (2011) achieved an increase of 41% in NHV after bio-drying, from 2731 to 4010 kcal kg^{-1}. Colomer-Mendoza et al. (2013) obtained an increase of 419.73% and 243.5% in NHV, 2021 kcal kg^{-1}, and 3276 kcal kg^{-1}, respectively. Shao et al. (2010) achieved a 157% increase in NHV after bio-drying. They found that NHV was directly related to plastics and paper content, which have higher LHV than food waste. After bio-drying, Martínez et al. (2013) observed NHV values between 3824 - 5019 kcal kg^{-1}, which is generally a fuel with commercially acceptable caloric content.

Particle size

The granulometric analysis made it possible to observe the particle size present in the SMSW (Figure 7). More than 85% of the particles were larger than 12.7 mm, both in the input and output material. Larger particles cause larger voids in the waste, favoring the passage of air between its particles (Kristanto & Zikrina 2017). Besides, particle size influences gas exchange and may interfere with biomass temperature, as it hinders or facilitates airflow (Stuart et al. 1999, Colomer-Mendoza et al. 2012). Kristanto & Zikrina (2017) evaluated moisture in three bio-drying tests and found that the most significant

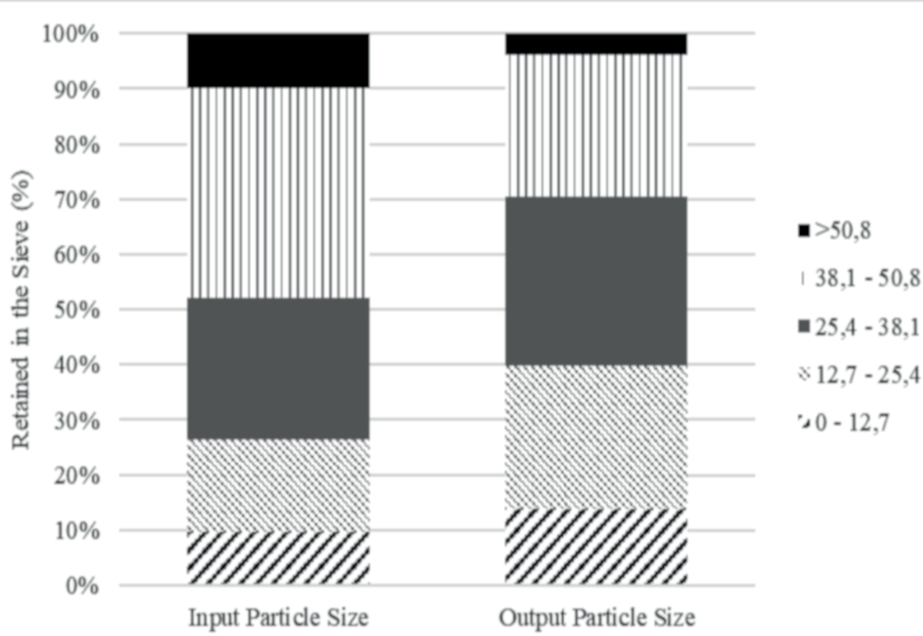

Figure 6. Net heating value of SMSW.

reduction (37.3%) occurred in the test with a granulometry of 100 - 300 mm. Given the above, the particle size may have favored the reduction of SMSW moisture content through convection.

CONCLUSIONS

To study the bio-drying process, rotating drums were built, and the residues submitted to evaluation were synthetically prepared, containing 60% of organic matter. During bio-drying, no increase in the SMSW mass' temperature was observed due to the degradation of organic matter by microorganisms, possibly due to the high aeration rate and the low amount of volatile solids. However, the moisture content decreased by 71%, 73%, and 81%, supposedly by convective evaporation. Particle size may have contributed to convective evaporation, since larger particles leave larger spaces in the medium, facilitating the passage of air between them. As a high moisture content was removed through the bio-drying process, the output NHV increased by 95%, 88%, and 122% for drums 1, 2, and 3, respectively, corresponding to 4557, 4694, and 4865 kcal kg^{-1}. In this process, despite the high moisture content, no leachate generation was observed.

The preliminary results of the bio-drying process using a rotary drum have shown promise. In this way, bottlenecks such as moisture content gradients and heating power can be eliminated from the process, contributing to this technique's large-scale use.

The bio-drying employment can help increase the useful life of landfills, as well as contribute to the global energy matrix, partially or entirely replacing non-renewable sources of energy.

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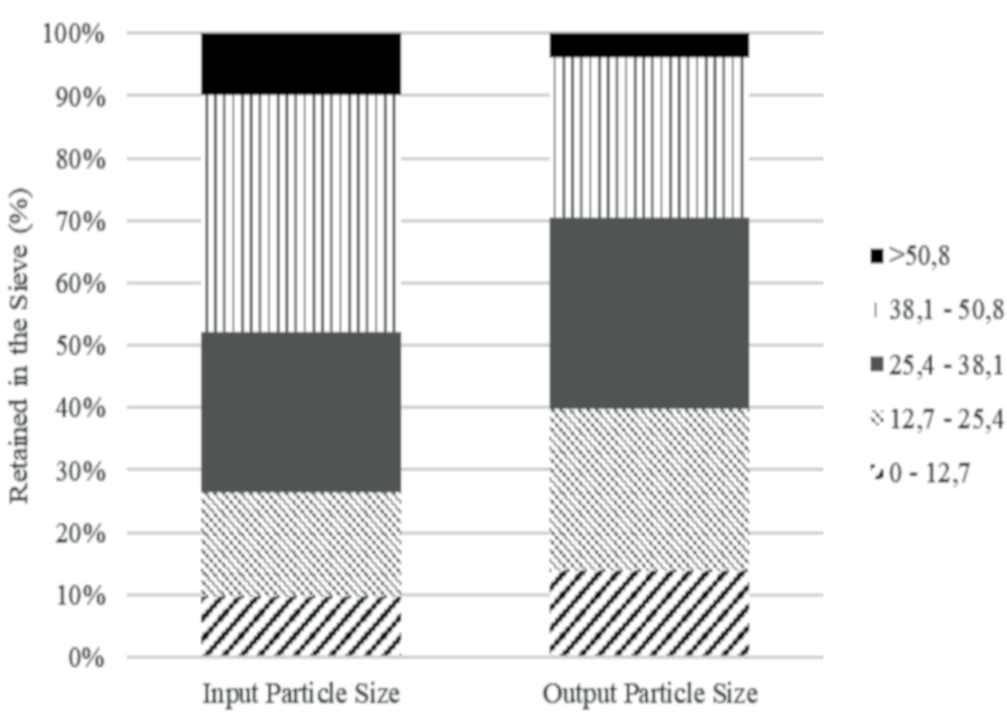

Figure 7. Particle size distribution of SMSW.

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