

Article

Behavior of Rejects from a Biological-Mechanical Treatment Plant on the Landfill to Laboratory Scale

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Abstract: This paper describes the laboratory-scale simulation of the behaviour of rejects from a biological-mechanical treatment (BMT) plant in Castellón (Spain). For this purpose, four lysimeters were built, with different densities. Simulations were carried out for 7 weeks and leachate recirculation was applied to two of them. The experimental results allowed us to determine: (i) dirt in fractions, which was relatively high (up to 15% in some fractions) due to biological processes; (ii) the field capacity for this waste with similar values to other works, which varied depending on the experiment; (iii) variation in the biomass percentage which lowered after experiments in all cases (59.5% lower on average), and the rejects' calorific value was higher after experiments (28.2% on average); (iv) the evolution of leachate properties with or without recirculation, where percolation, in addition to the dragging of soluble materials, stabilised waste, which diminished its biological activity. Rejects' increased calorific value will allow combustible material to be recovered in the future as a way to exploit the energy potential stored in landfills.

Keywords: BMT plants; rejects; landfill; lysimeter; leachate; LHV

1. Introduction

According to the waste management hierarchy, landfilling is the least preferable option and its use should be kept to an absolute minimum. Therefore, following European Union regulations, waste must be treated before being landfilled [1]. Public acceptance of waste disposal sites is not widespread, owing to concerns about their adverse effects on both the environment and human health, and populations living near landfills often feel apprehension [2]. The treatment of municipal solid waste (MSW) in mechanical biological treatment (MBT) or biological mechanical treatment (BMT) plants allows a significant proportion of materials to be recovered and recycled (recyclable materials like plastics, paper-cardboard, metals, etc., on the one hand, and biowastes on the other hand) [3]. However, another important fraction of MSW cannot be recovered and is considered to be reject.

In BMT plants, when MSW arrives at facilities, it is shredded and then the bulk waste is fermented aerobically by a biological process (biodrying). Next, different fractions (plastics, paper-cardboard, metals, glass, etc.) are separated manually or mechanically, and the organic fraction (already stabilized) is ripened in a covered area. In MBT plants, MSW is subjected to mechanical treatment where biowaste recyclable fractions are separated. Next bio-waste is composted.

The characteristics of the rejects from both BMT and MBT plants differ from those of MSW, because the biodegradable and recyclable fractions have been removed [4]. In Spain, the rejects from MBT plants represent about 65%–75% of the volume of the initial MSW and are usually incinerated as a solid, which is recovered as fuel, or, above all, is landfilled [5–7]. There is only one BMT plant in Spain, but such treatment is somewhat more widespread in other countries like Italy.

In some regions of Europe, rejects are normally used as waste-derived fuel (WDF) because it usually contains large amounts of combustible material, such as plastic film, paper-cardboard and textile (cotton, wool, Lycra, etc.), which can be a future source of fuel. The technique used to recover these materials is known as landfill mining [8]. However, if the fate of rejects after disposal is landfill mining, it is advisable to know how combustion performance and the environmental impact vary after applying some feasible supplemental measures, such as waste pretreatment and an advanced pollution control system [9]. Given the high cost of incineration plants, rejects in the majority of EU countries are usually landfilled. Nevertheless, to date, the behaviour of landfills for rejects has not been studied very much.

Landfilled rejects usually consist of different flows of rejects from BMT or MBT plants, depending on treatment type and the quality of the resulting material. Once rejects have been landfilled, they start to undergo a series of physical-chemical processes due to changes in moisture (short term) and anaerobic fermentation (mid to long term). Moreover, generation of leachate is one of the main potential environmental impacts caused by both sanitary landfills and landfills for reject material and lead the volume and characteristics of the leachate to differ in the latter.

Moisture strongly influences degradation times in sanitary landfills [10] and field capacity (FC) can vary depending on several factors, such as the density, age and composition of waste. FC determinations allow the volume of water retained in the waste mass to be estimated.

Recirculation of leachates, if controlled, is a very frequently applied technique for accelerating the decomposition rate of MSW [11], reducing the volume of leachates by evaporation and improving the thermal conditions in bioreactors to typical mesophilic values [12]. Leachate percolation probably improves the distribution of substrates or nutrients in the waste bed by accelerating biodegradation [13]. In other words, leachate recirculation accelerates the decomposition rate of MSW [11]. Moreover, continuous washing with water is essential for removing leachable organic matter and soluble nutrients from the fine fraction and for increasing the collected leachate volume [14]. According to Öman and Hynning (1991) [15], recycling of leachate promotes the internal mechanisms responsible for waste stabilization and leachate treatment. The reintroduction of necessary nutrients, such as phosphorus and nitrogen, enhances the growth of the microbial population and affects the extent of stabilization [16].

High recirculation rates may, however, adversely affect the anaerobic degradation of solid waste [17,18].

In the literature, no such simulations done with rejects from BMT plants are found, which implies that studying rejects with treatment is not sufficient. Most of the research in which lysimeters with waste have been used has been conducted with MSW, even in recent years. In addition, the calorific value of the waste contained in landfills has rarely been studied and most research has focused on studying biogas generation, waste degradation, the generation and properties of leachate or knowing settlements. For example, Chung et al. (2019) [19] analysed the influence of waste composition on landfill gas generation in a pilot-scale lysimeter using seven different waste types. Aljaradin and Persson (2016) [20] conducted a comprehensive study to monitor the emission potential from solid waste landfilled in Jordan using an anaerobic lysimeter. Godio et al. (2015) [21] developed a small-scale lysimeter which was set up to simulate the biological processes that take place in a bioreactor landfill with rejects from an MBT plant under laboratory conditions.

Lavagnolo et al. (2018) [22] experimented on the potential dual-step management of semi-aerobic landfilling in a tropical climate with MSW, where they reproduced the composting process during the dry season and subsequently flushed (a high rainfall rate) during the wet period. Wu et al. (2016) [23] constructed three pilot-scale lysimeters which were operated for 4.5 years to quantify the change in carbon and nitrogen pools in an old landfill under various air injection conditions. Slezak et al. (2015) [24] studied the degradation of MSW in simulated landfill bioreactors under aerobic condition to investigate leachates from a landfill. Once again, the employed substrate was MSW. Dabrowska et al. (2019) [25] employed a lysimeter to study the size and chemical composition of leachates, as well as the leachate water balance of an MSW landfill. Van Turnhout et al. (2018) [26] theoretically analysed MSW treatment

by leachate recirculation under anaerobic and aerobic conditions. These authors described the emission data measured during aerobic and anaerobic leachate recirculations in lysimeters. Wu et al. (2012) [27] set up pilot-scale lysimeter experiments run in different aeration modes to obtain detailed information about the influence of aeration modes on leachate characteristics. Sutthasil et al. (2014) [28] compared solid waste stabilisation and methane emissions from anaerobic and semi-aerobic landfills operating under tropical conditions. Araujo et al. (2017) [29] statistically modelled an MSW settlement with a lysimeter, while Melo et al. (2016) [30] examined the settlement behaviour of MSW according to the internal/external environmental factors in a lysimeter.

Moreover, dirty materials are normally used when such research is carried out [5,7,8]. Depending on the origin of the waste (mixed waste, rejects, etc.) and treatment type (biomethanation, BMT or MBT), existing materials (wood, paper and cardboard, plastic, etc.) can contain a significant amount of dirt due to the mixture of mainly organic waste and other types of dirt like inert material (soil, dust, sand, ash, etc.). The amount of material that accompanies the materials making up rejects depends on the process that has generated rejects. For example, rejects from a manual waste packaging selection contain less dirt than those obtained from refining compost. The amount of dirt in rejects can lead to different properties and compositions in leachates when they have been landfilled. Nevertheless, this aspect has not yet been adequately studied, although some works demonstrate that removing dirt in waste by washing can reduce the contaminant charge of leachates (chlorides, sulphates, fluoride and metals) by approximately 60% [31].

Thus, although simulations have often been carried out using lysimeters, they have been done with MSW and not with rejects. In this work, the behaviour of rejects was evaluated to determine the leachate's volume and characteristics and the evolution of the physico-chemical properties of rejects. These objectives were sought by simulating the behaviour of landfilled rejects from a BMT plant on the laboratory scale. The FC of reject with a known density, volume and characteristics of generated leachates and the evolution of the properties of the rejects (biomass and non-biomass content, low heating values (LHV) and ashes) were determined to supply data for this sort of landfill with or without leachate recirculation. The novelty of the present work lies in it determining the dirt that accompanies all the fractions making up rejects. Dirt contributes organic matter and other components, which can affect both the biodegradation process inside the landfill and the composition of the leachates.

2. Materials and Methods

Rejects were obtained from a BMT plant in Eastern Spain. The plant generates 65,000 t/year of rejects, which represents 73.27% of the MSW inlet [6]. The MSW is submitted to a biodrying process when it arrives at the BMT plant. Figure 1 shows the general flow of reject, which is divided into three smaller flows with the following percentages: 44% from the reject from the recyclable materials recovery process (Flow A: particle size > 80 mm); 42% from the refuse before the biostabilised material refining process (Flow B: particle size 80–25 mm); and 14% from the biostabilised material refining process (Flow C: particle size 25–8 mm).

The experiment consisted of four steps: sample collection; initial determination of rejects' properties; construction and filling of four lysimeters; experimental phase.

2.1. Sample Collection and Physical Characterisation

The samples of reject flows were collected following the procedure described by Edo-Alcon et al. (2016) [5]. Pieces were crushed to a maximum size of 7 cm, mixed in the above-cited proportion and characterised according to the methodology described in SWA-Tool [32].

Part of the sample (5 samples of 5 kg each) was taken to determine the dirt in its components. The same fractions as those shown in Table 1 were separated and dried. The dirt in all the fractions was determined by washing them with soap and water and then quenching them with deionised water. They were then dried again and the difference in weight before and after cleaning was calculated. Five common dirt samples were extracted from all the fractions, and ash and volatile solid contents

were determined following CEN/TS 15,403 (2011). Finally, the mean and standard deviation of each fraction were calculated.

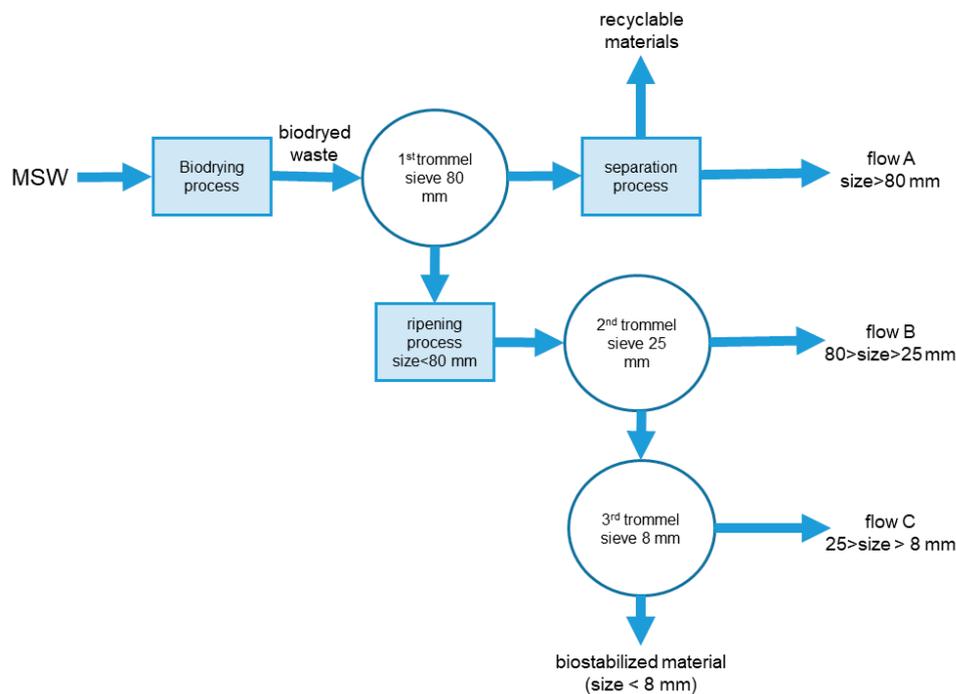


Figure 1. Classification of rejects in a biological-mechanical treatment (BMT) plant according to size.

Table 1. Physical composition (dirty and clean waste) of rejects and dirt in materials (dry weight; d.w.).

Materials	Physical Composition Dirty Material %	Dirt in the Waste (%)		Physical Composition Clean Material%
		Mean	Standard Deviation	
Organic waste	12.95	—	—	25.53 *
Wood	2.85	15.16	5.19	2.42
Paper and cardboard	25.12	9.77	2.21	22.67
Plastic	29.21	11.23	1.95	25.93
Glass	3.76	7.59	2.01	3.48
Textile	16.02	13.49	2.03	13.86
Metals	3.55	10.76	4.56	3.17
Hazardous waste	0.02	—	—	0.02
Inert	3.25	3.52	1.98	3.25
Others	3.27	9.56	5.21	2.96

* organic waste and total dirt.

2.2. Initial Determination of Rejects' Properties

Moisture content was determined following standard ISO 24557:2009. The LHV was analysed by isoperibol calorimeter PARR model 1261 according to standard CEN/TS 15,400 (2006). Biomass and non-biomass contents (Equation (1)) were established following European standard EN 15440: 2011. Ash content was established following standard CEN/TS 15,403 (2011). All the analyses were performed in triplicate. Finally, the mean and standard deviation of each parameter were calculated.

$$\text{Non-biomass content (\%)} = 100 - \text{biomass (\%)} - \text{Ashes (\%)} \quad (1)$$

2.3. Construction and Filling of the Four Lysimeters

Four similar lysimeters were assembled for the assay. The structure of all the lysimeters consisted of a polyvinyl chloride (PVC) pipe (diameter of 110 mm; Figure 2). A perforated PVC plate made with a layer of geotextile was fitted on the bottom of the pipe to allow the leachate to flow into a collection bottle. The PVC pipe was filled with a mixture of different rejects. They were compacted with the help of a perforated PVC plate on the top of the pipe. In two of the lysimeters (1 and 2), a density of 400 kg/m^3 was established, while density was set to 500 kg/m^3 in the other two (3 and 4).

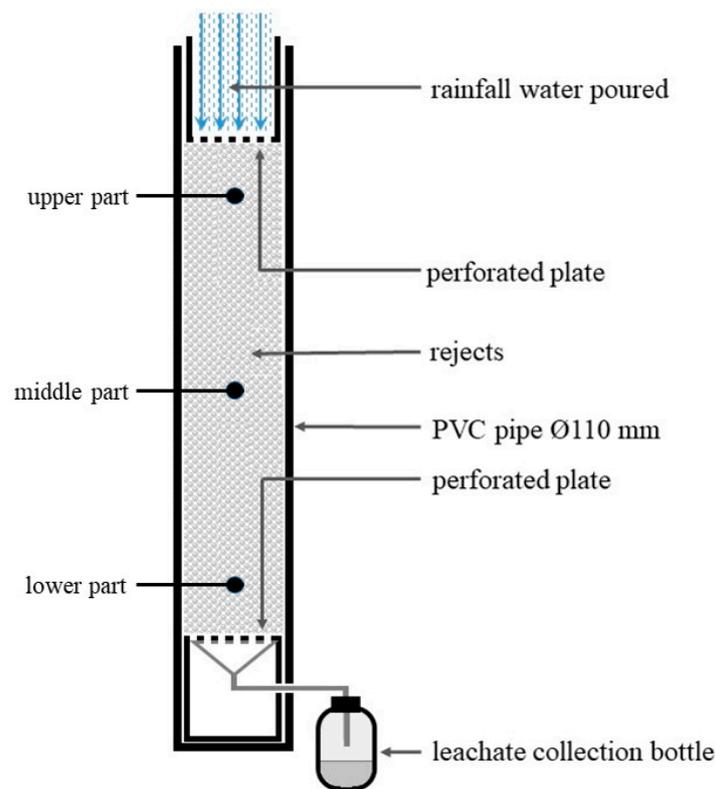


Figure 2. Scheme of the lysimeter.

2.4. Experimental Phase

Once the required density had been obtained, FC was calculated by Equation (2) [4] 24 h after the first irrigation. Then, the evolution of the rejects was registered for 42 days. This is the average duration of the heavy rains period in a region with a Mediterranean climate, when 60% of the yearly rainfall occurs (290 L/m^2). This period usually coincides with September and October.

$$FC = \frac{H_{R0} \cdot D_{R0} \cdot V_{R0} + (V_{I1} - V_{F1})}{(1 - H_{R0}) \cdot D_{R0} \cdot V_{R0}} \quad (2)$$

where FC is the field capacity of the refuse ($\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{dry reject}}$); H_{R0} is the initial moisture of the refuse mass ($\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{reject}}$); D_{R0} is the initial density of the refuse mass ($\text{kg}_{\text{reject}}/\text{m}^3$); V_{R0} is the volume of reject inside the lysimeter (m^3); V_{I1} is the volume of water added to the lysimeter ($\text{kg}_{\text{H}_2\text{O}}$); and V_{F1} is the volume of leachate collected 24 h after the first irrigation ($\text{kg}_{\text{H}_2\text{O}}$).

In order to forecast leachate generation in a Mediterranean climate, a volume of distilled water equivalent to the seasonal rainfalls was poured into the lysimeters. At the beginning of the assay, 1.30 L of water was added to reach FC. The rest of the water was allocated by means of weekly fractions of 0.25 L (the equivalent to $26 \text{ L/m}^2 \cdot \text{week}$) to reach 2.8 L. Furthermore, in 2 and 4, with densities of 400 and 500 kg/m^3 , respectively, the leachate was recirculated. The leachate thus generated was measured

weekly using a calibrated cylinder. In each measurement, conductivity, total solids, pH and COD were determined. After 42 days, the samples were extracted and weighed and the moisture, ashes, LHV, biomass and non-biomass content were determined in the upper, the middle and lower parts (Figure 2), in accordance with the same above-cited standards.

3. Results and Discussion

3.1. Physico-Chemical Characterisation of the Initial Reject

The average percentages of fractions after characterising the different flows of the rejects from the BMT plant are shown in Table 1. Lysimeters were filled according to this proportion.

Table 1 also shows the percentage of dirt accompanying each fraction that formed part of rejects. As can be observed, the percentages of dirt were high, and represented up to 15% (dry weight; (d.w.)) for wood (hazardous waste was not found in the five samples). The percentages were high due to the design of the analysed plant because the biodrying/fermentation stage was carried out with all the waste mixture and therefore, the biological decomposition of biodegradable waste causes significant soiling in the remaining fractions (paper-cardboard, glass, plastic, textile, etc.). Thus, dirt was composed mainly of biowaste and inert solids (dust, soil and sand). This poses a major landfill management concern as it increases the degree of pollution in leachates and biogas generation. Therefore, washing waste is a feasible pre-treatment method that focuses on controlling the leachable fraction of waste and the relevant impact [31]. However, the proportion of dirt in waste has not been sufficiently studied in the literature.

As expected, although the biodegradable matter was removed in the BMT, the biodegradable part in rejects (even including dirt) was much lower than in MSW, which, in this work, was around 13%. This value is far lower than those reported by Aljaradin and Persson (2016) (52%) [20], Araujo et al. (2017) (47%) [29], Lavagnolo et al. (2018) (53%) [22] and Slezak et al. (2015) (55%) [24].

In rejects, the most abundant waste types were plastic (especially 90% film) and dirty paper-cardboard. As this type of plastic (film) is difficult to recycle, it remains a reject. The percentage of paper-cardboard was high because it is a dirty material with pieces of degraded food attached to it and not originally separated. Additionally, despite the fact that a separate collection system existed in the area, the textile content was also high.

The chemical characterisation of the initial reject is shown in Table 2. Moisture was lower than in the rejects from an MBT plant as this sort of BMT plant applies biodrying before mechanical separation. The moisture of the rejects from the mechanical process of typical MBT plants in Spain ranges from 30% to 35% [5,6], and is about 25%–30% in Italy [21], and 30.2% in Thailand [28]. However, it was 17%–21% for rejects in the present work. Conversely, the moisture in other works conducted with lysimeters (with MSW as a substrate) was 52% [20], 41.1% [32], 41% [21], 40.4% [23], 32% [24] and 29.3% [25]. Therefore, in landfills with rejects from BMT plants, the waste mass reaches the FC later because of the lower moisture, and it would take longer to generate leachates.

Table 2. Properties of rejects at the start and at the end of the assay (d.w.).

Start of the Assay		End of the Assay (400 kg/m ³)				End of the Assay (500 kg/m ³)					
Parameters		Initial Rejects		Lysimeter 1		Lysimeter 2		Lysimeter 3		Lysimeter 4	
ID	Ud	\bar{x}	$\bar{\sigma}$	\bar{x}	$\bar{\sigma}$	\bar{x}	$\bar{\sigma}$	\bar{x}	$\bar{\sigma}$	\bar{x}	$\bar{\sigma}$
Moisture	%	19.65	2.36	60.93	4.62	59.50	7.72	59.34	2.01	58.35	7.86
Biomass	%	50.47	3.19	28.65	0.21	30.68	4.68	30.89	0.54	29.83	1.79
Non-biomass	%	15.17	1.67	28.92	0.67	29.99	1.55	28.60	0.14	28.75	1.38
Ashes	%	34.36	2.16	45.52	5.74	40.10	3.77	45.20	5.62	39.82	3.19
LHV (d.w.)	MJ/kg	11.26	0.73	15.02	4.63	13.99	2.03	14.74	4.81	14.06	1.83
LHV (w.w.)	MJ/kg	9.06	0.58	5.87	0.17	5.83	0.11	5.99	0.15	5.86	0.24

The biomass content was about 50%. It contains mainly organic waste, paper-cardboard, textile (above all cotton and wool) and wood. The ash content of the complete rejects was about 34% because rejects contained a large amount of glass, metals, inert and dirt. Dirt had an ash content of about 30%, due mainly to the soil, dust and sand in its composition. Finally, LHV (d.w.) was not as high as expected because rejects contained a large amount of ash. Edo-Alcon et al. (2016) [5] determined an LHV of 200 MJ/kg (d.w.) for rejects with 91.6% combustible material and 22.4% ash for the combustible fraction. Other works, like those by Hemidat et al. (2019) [33], indicated an LHV of 15.6 MJ/kg and 16.7%–19.6% ash after a biodrying process. Hidalgo et al. (2019) [34] determined an LHV of 23.2 MJ/kg (d.w.) and 15.7% ash from rejects from MBT plants. Nevertheless, in the work of Drudi et al. (2019) [35], the LHV in waste extracted from a Brazilian landfill was 7.03 MJ/kg (w.w.). Chan et al. (2019) [36] reported an LHV of 23 MJ/kg (d.w.) and 10.5% ash (d.w.) for refuse-derived fuel pellets from rejects.

3.2. Determination of the FC of Rejects

The FC of landfilled waste can simply be explained as the moisture content at which the maximum amount of water is held by the waste against gravity, after which leachate would be produced. The FC depends on the waste composition, particle size and degree of compaction [37,38]. The resulting values after analyses and calculations for the four lysimeters are summarized in Table 3. According to this table, the average FCs obtained from lysimeters 1–2 and 3–4 were 1.16 kg_{H2O}/kg_{dry reject} and 1.09 kg_{H2O}/kg_{dry reject} with densities of 400 and 500 kg/m³ respectively. These data are similar to the interval calculated by Orta de Velasquez et al. (2003) [39], who reported that FC was inversely proportional to the density of waste. They calculated a value of 1.17 kg_{H2O}/kg_{dry waste} for a density of 350 kg/m³ in the waste mass of a Nuevo Laredo landfill (Tamaulipas, Mexico). Aguilar (2008) [40] calculated the FC of waste (1.02–0.84 kg_{H2O}/kg_{dry waste}) according to its density (0.39–0.80 t/m³, respectively) and Cox et al. (2015) [41] 0.45–1.08 kg_{H2O}/kg_{dry waste} from different compactions. Dollar (2005) [42] did the same and obtained FC values of 0.72–0.46 kg_{H2O}/kg_{dry waste} and density values of 0.30–1.03 t/m³. Wu et al. (2012) [27] indicated that FC varied according to the pressure of waste, whereas Jayakody et al. (2014) [43] showed that water retention characteristics in the solid waste landfill environment varied with time and were influenced by landfill settlement due to changes in pore spaces. These values obtained for rejects in a simulated landfill are similar to those taken from studies involving MSW landfills. Nevertheless, it should be noted that the composition of fractions vastly varies and therefore, the evolution of rejects over 42 days could also substantially differ.

Table 3. Field capacity of the four lysimeters.

ID	Parameters	Units	Lysimeter 1	Lysimeter 2	Lysimeter 3	Lysimeter 4
D _{R0}	Initial density	kg/m ³	400	400	500	500
H _{R0}	Initial moisture	%	19.65	19.65	19.65	19.65
V _{R0}	Initial volume of rejects	m ³	2.68·10 ⁻³	2.68·10 ⁻³	2.17·10 ⁻³	2.17·10 ⁻³
V _{I1}	Volume of water added on the first day	L	1.30	1.30	1.30	1.30
V _{F1}	Volume of leachate on the first day	L	0.52	0.50	0.57	0.58
FC	Field Capacity (initial)	kg _{H2O} /kg _{DRY W}	1.15	1.17	1.09	1.08
FC	Field Capacity (final)	kg _{H2O} /kg _{DRY W}	1.56	1.47	1.46	1.41
	Final volume of leachate	L	1.57	1.40	1.73	1.38

The differences between the FCs in lysimeters 1–2 and 3–4 (densities of 400 and 500 kg/m³ respectively) were not much larger at the end of the experiment (5.3%) than at the beginning (6.5%) but according to Table 3, FC had increased by the end of the experiment (31.4% on average). This was probably because particle size had changed after 42 days due to the initial degradation of slowly biodegradable material (especially paper and cardboard). As a result, the pore size in the waste mass would also have changed and there would be a bigger proportion of pores at the end of the experiment than at the beginning.

3.3. Influence of Recirculation on Rejects' Properties

The generated flow of irrigation and leachate is shown in Table 4. In lysimeters 1 and 3, the poured influent was water, but in lysimeters 2 and 4, the influent was water plus the generated leachate, which was recirculated. The final poured water and generated leachate is shown in the bottom row of Table 4. According to the final leachate balance, if leachate had been recirculated (to prevent evaporation), the lysimeter would have generated less final leachate (18.7% less on average). Table 2 includes the properties of rejects (LHV, biomass content and non-biomass content) at the beginning and at end of the experiment.

Table 4. Water poured into the lysimeters and the leachate generated in litres (w: water; l: leachate).

	Lysimeter 1		Lysimeter 2		Lysimeter 3		Lysimeter 4	
	Influent (w)	Effluent	Influent (w + l)	Effluent	Influent (w)	Effluent	Influent (w + l)	Effluent
1st day	1.300	0.520	1300 (w) 0.500 (l)	0.500 0.280	1.300	0.570	1300 (w) 0.580 (l)	0.580 0.400
1st week	0.250	0.110	0.250 (w) 0.440 (l)	0.160 0.317	0.250	0.134	0.250 (w) 0.565 (l)	0.165 0.350
2nd week	0.250	0.150	0.250 (w) 0.537 (l)	0.220 0.455	0.250	0.170	0.250 (w) 0.520 (l)	0.170 0.465
3rd week	0.250	0.175	0.250 (w) 0.700 (l)	0.245 0.665	0.250	0.180	0.250 (w) 0.685 (l)	0.220 0.650
4th week	0.250	0.180	0.250 (w) 0.915 (l)	0.250 0.905	0.250	0.190	0.250 (w) 0.900 (l)	0.250 0.885
5th week	0.250	0.205	0.250 (w) 1.155 (l)	0.250 1.150	0.250	0.235	0.250 (w) 1.135 (l)	0.250 1.130
6th week	0.250	0.230	0.250 (w)	0.250	0.250	0.250	0.250 (w)	0.250
FINAL BALANCE	2.800	1.570	2.800	1.400	2.800	1.729	2.800	1.380

Biomass, non-biomass, ash and LHV were analysed to determine the evolution of rejects' properties. These analyses were performed at three levels in the lysimeters, as shown in Figure 2 (upper, middle and lower parts), which made it possible to determine the washing/leaching of the materials over the period.

Leachate dragged biomass, as indicated by the fact that biomass content was lower after the experiment in all cases (59.5% lower on average). What this demonstrated was that after irrigation, organic waste, dirt and soluble substances are washed down by the leachate. Recirculation of leachates (lysimeters 2 and 4) made the proportion of biomass more homogeneous in height, but biomass dropped to the lowest levels (Figure 3) if rejects were washed with clean water (lysimeters 1 and 3). Although recirculation took place, biomass went down more slowly in lysimeter 4 because its density was higher: upper part (38% of biomass), middle part (29.8%) and lower part (28%).

According to Figure 3, the rejects in the lower part of the four lysimeters had a higher percentage of ash (23.8% higher on average), which means that as the leachate went down, inert solids (soil, dust and sand) were dragged with it.

Therefore, slowly biodegradable material like plastic, textile, etc., remained in the reject mass and the LHV was higher after the experiment because of this (28.2% on average). Conversely, although the ash content was lower after the experiment in the lysimeters with recirculated leachates (12.4% lower on average), the LHV was also lower (5.7% lower on average) because more organic waste and dirt remained in the reject mass.

Nevertheless, the rejects in the upper part of lysimeters 1 and 3 had higher LHV and non-biomass values (Figure 3). This meant that clean water washes rejects better than leachate and it dragged the ash and biomass materials with it, while the non-biodegradable and non-soluble material remained in the upper part. In the lysimeters with leachate recirculation, the LHV was more homogeneous in height as the recirculated leachate dragged solids. Therefore, in this case, the recirculation of leachates would not be advisable to recovering rejects as fuel in the future. Notwithstanding, washing with

water would drag the dirt of waste, which had a high percentage of inert material (around 30%) and would not only accelerate biodegradation, but also decrease ash and increase the LHV of waste.

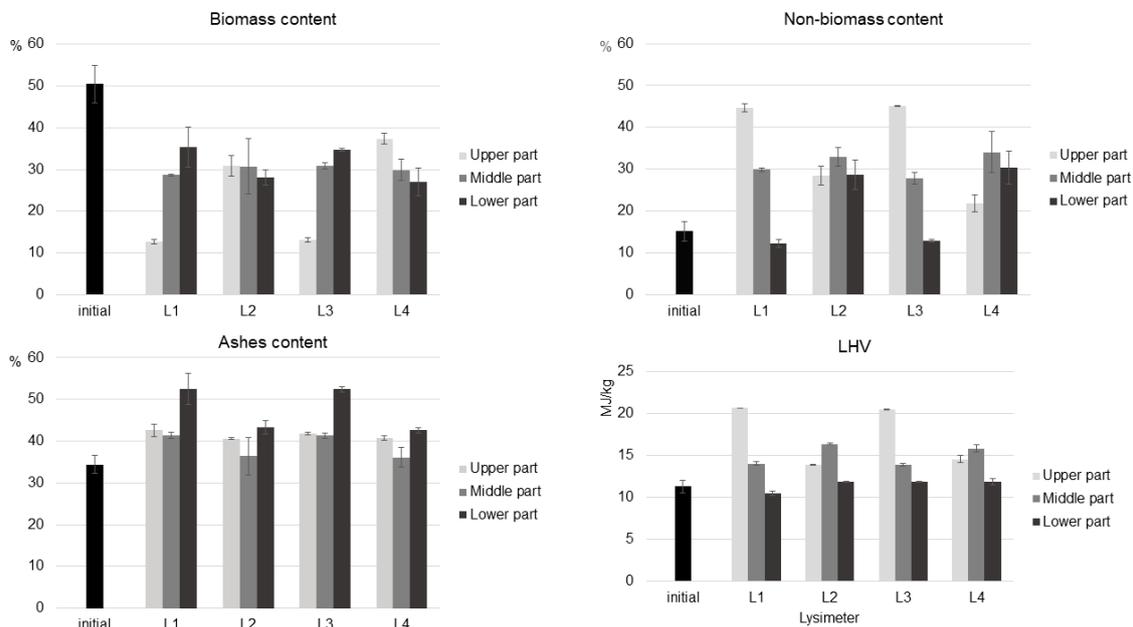


Figure 3. Chemical properties rejects before and after the experiment.

3.4. Properties of Leachate Evolution

Volume, the parameters related to the leachate generated, water balance and their evolution over 42 days are shown in Table 4 and Figure 4. Table 4 indicates the water irrigation schedule and Figure 4 offers details of the evolution of chemical properties, such as conductivity, pH, COD and total solids.

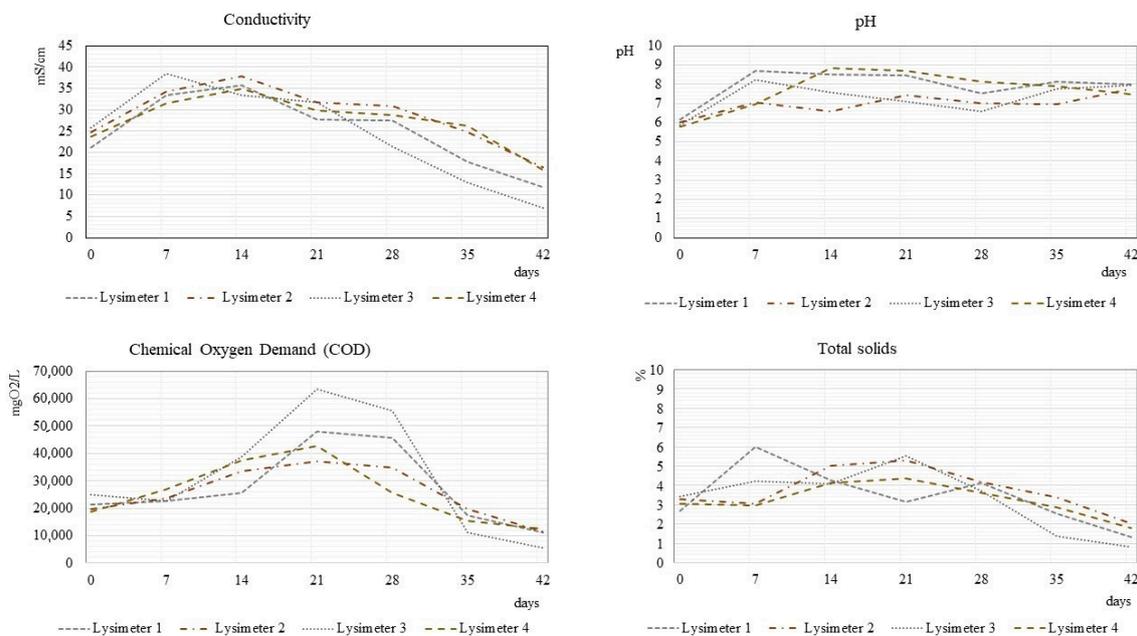


Figure 4. Chemical properties of leachate over 42 days.

Lysimeters 1 and 3 collected more leachate than lysimeters 2 and 4. Lysimeter 1 collected 10.8% more than lysimeter 3, and lysimeter 2 collected 20.2% more than lysimeter 4. This could be because recirculation caused the leachate to have more total solids (TS), mainly due to the dirt of rejects and

their high inert material contents. If no recirculation took place, greater mass loss would occur and therefore, the FC would be higher. Moreover, recirculation caused a bigger amount of solid materials to be retained, which led to lower FC (Figure 4).

Conductivity displays a similar behaviour in lysimeters 1, 2 and 4 and its maximum level was reached on day 14. As washing was greater in the lysimeters without recirculation, conductivity lowered more quickly as of day 25. In lysimeters 2 and 4, conductivity remained high until day 36. However, lysimeters 2 and 4 had a higher conductivity than the non-recirculated ones. In fact, at the end of the experiment, the average conductivity in the lysimeters without recirculation was 41.7% lower due to washing the waste mass. These data are similar to the results obtained from fresh leachate in landfills, like those offered by Tatsi and Zouboulis (2002) [44], with values of 23.0–35.5 mS/cm, 8.6–23.7 mS/cm [45], 28.3 mS/m [46] or 35.2–42.9 mS/cm [47] 17.17–30.06 mS/cm [25] and 7.8–32.9 mS/cm [21]. They are higher than those from leachate of intermediate age (5–10 years), with values of 4.1–1.4 mS/cm [48] or 8.1–4.2 mS/cm [15].

Secondly, the pH remained constant in both cases (leachates with and without recirculation), at around 7–9, but these values became slightly acidic (pH 6.02 and 5.90 respectively) at the beginning of the test. From day 7 onwards, they became slightly alkaline and remained so until the end of the process. This could be because acidogenic activity was briefly restarted due to the presence of high humidity. When it finished, pH increased to around 7.5–8. No significant differences were noted in either case. pH usually remains constant when microbiological activity ceases, with neutral values of 6.5–7.0 [48], 5.7–8.0 [15], > 7 [49], 5.8–6.8 [50] and 6.63–7.18 [25]. Nevertheless, replacing the recirculated leachate with tap water helped to maintain a neutral pH [20] and the pH of the leachate became neutral after the acidogenic phase and the non-degraded waste ran-off in the leachate [19]. Normally, pH initially lowers due to the acidogenic phase in works performed by lysimeters with fresh organic waste and pH values could drop to values of 5 or even lower within 30 days [22].

Thirdly, COD notably increased until days 21–28, when high pollution levels were reached (63,425 mg/L) before considerable dropping. However, in the lysimeters without recirculation, the COD value is 29.1% lower when chemical and biological activity ceases. The values at the end of the experiment were similar to those of a leachate of an intermediate age with levels of 10,000–12,000 mg/L [48] or 18,380 mg/L [21], but with higher levels than those of old leachates with 4880 mg/L [44], 5350 mg/L [51], or 5280 mg/L [21], and with lower values than for fresh leachate, with 69,600 mg/L [44] or 70,900 [51]. It was assumed that waste degraded (biodegradable fraction) until the maximum values were reached in week 3. The recirculated ones underwent greater intermediate chemical and biological degradation when waste was washed with water. A higher recirculation rate for the leachate in lysimeters led to a more significant COD reduction than the lysimeters without recirculation. In fact, in Slezak's experiments [24], COD fell from 14,929 mg/L on day 7 to 950 mg/L at 40 days. Obviously, in experiments done using lysimeters with organic waste, the COD of leachate after 30 days was much higher than with rejects (up to 50,000 mg/L versus 3500 mg/L) [22].

Something similar happened with the TS in the leachate; that is, the values peaked (5–6%) on days 7–21, which is similar to those obtained by other authors: 5.3% [44] or 5.5% [51]. TS then decreased, but with values lower than the initial ones (62.9% lower and 39.7% lower on average, respectively), and similar to those reported by other authors: 1.2% [51] or 1.2% [52]. In lysimeter 1, washing was faster because it was less compacted than lysimeter 2.

The graphs in Figure 4 show that the conductivity of leachate, COD and TS dropped from day 21 onwards in all the lysimeters, which suggests that the leachate became less polluting as water was dragged salts, dirt, solids and soluble biomass. Continuous water washing was essential for removing leachable organic matter and soluble nutrients from the fine fraction and increased the collected leachate volume [14]. Zhao et al. (2006) [53] also reported that recirculation could dramatically improve the quality of the leachate with lower COD, TS, $\text{NH}_4(+)$ -N and higher pH values. Recirculation could also enhance waste degradation and stabilisation and improve landfill efficiency [54]. Something similar was presented by Lou et al. (2014) [9], who claimed a close relation between the state of refuse

decomposition and its associated leachate characteristics. Microbiological activity also seemed stable throughout the experiment, as the pH value remained constant.

Moreover, the control of these fluid flows is a key issue in the landfill management, specifically when a bioreactor process (recycling leachate to accelerate the biodegradation rate) is applied [55]. In fact, leachate recirculation in MSW landfills operated as bioreactors offers significant economic and environmental benefits [56]. Notwithstanding, Bilgili et al. (2007) [57] remarked that the positive effect of leachate recirculation is more clearly observable in anaerobic landfill operations than in aerobic landfills. Recirculation is more effective in anaerobic solid waste degradation than in aerobic degradation. In the present work, this fact is less important because rejects had less biodegradable material content and the effects were not so important.

The results herein obtained are similar to those reported for MSW landfills, but this research used rejects with much less biodegradable material. Hence, a faster decrease in the contaminant parameters was expected [58]. In any case, the wide spectrum of each in real landfills parameter demonstrates the huge heterogeneity of the leachate, which can be influenced by season and weather [21].

4. Conclusions

In this work, rejects from BMT plants were studied in a lysimeter. In such rejects, the proportion of the biodegradable part is much smaller because it was removed during mechanical treatment, and moisture was much lower as it had undergone a biodrying process. Thus, rejects took longer to reach FC and to, therefore, generate leachates. Furthermore, the dirt of rejects after the biodrying process was determined to estimate the leachate's polluting load.

It was possible to verify how the infiltration and percolation of water through waste mass (rejects) dragged a remarkable proportion of biomass and dirt in a short period of time. This percolation, in addition to dragging the soluble materials, stabilised the wastewhose biological activity diminished. Likewise, the leachate's salt, COD and TS contents reduced as of experiment day 21, as in other similar works. Consequently, waste stabilization could minimise the environmental impacts caused by the leachate and biogas in landfills for longer periods of time.

Conversely, the dragging of biomass, dirt, inert solids and salts increased the LHV of the reject mass in all cases. This increase would have been more effective if recirculation with leachate had not applied. In fact, washing rejects with tap water, similarly to rainfall, dragged a larger amount of dirt. These results are interesting to study the feasibility of processing rejects confined in landfills in order to transform them into solid recovered fuels, known as "landfill mining".

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