



Optimization of the Biostabilization Process of an Italian Mechanical–Biological Treatment Plant to Account for Changes in Waste Composition

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Abstract

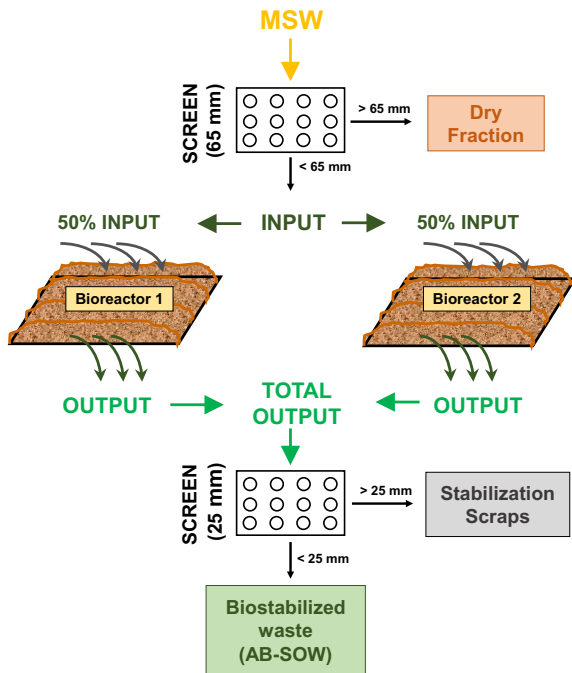
In this paper, we present a case study on the optimization of the biostabilization process of an Italian mechanical–biological treatment (MBT) plant to account for changes in feed waste composition related to a progressive increase in separate collection of MSW fractions, biowaste in particular. After ten years of operation (2009–2019), a decrease of the stabilization degree of the output material of the plant was detected, with Dynamic Respiration Index (DRI) values above the established limit of 1,000 mgO₂/kg_{Vs}/h (average values of 4,000 mgO₂/kg_{Vs}/h determined weekly for eight weeks). The investigations carried out in 2019 on the waste samples feeding the MBT plant showed that paper and plastic materials constitute around 75% of the input waste to the two aerobic bioreactors of the MBT plant, against 55% at the start-up (2009). Furthermore, the airflow rates and the moisture content analyzed weekly for eight weeks in the bioreactors resulted below the optimal values suggested in the literature. To improve the performances of the biostabilization process, a series of modifications were implemented in the plant. The main modification involved the primary mechanical treatment by varying the mesh size of the screens to 50 mm circular holes mesh. Furthermore, the configuration of the aerobic bioreactors was changed by placing the two bioreactors in series (instead of the previous configuration in parallel) and using a screening unit (25 mm) between the two bioreactors instead of at the end of the process. In this way, the residence time of the materials in the aerobic treatment was enhanced from 16 days with the previous configuration to 27 days. Together with an increase of the airflow rates of around 40% and a water supply of approximately 10% in the bioreactors, these modifications allowed to achieve the desired stability of the output waste, with DRI values below 1000 mgO₂/kg_{Vs}/h.

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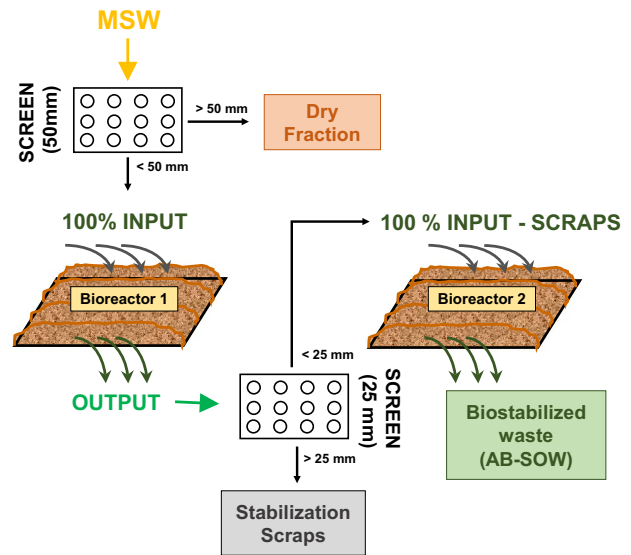
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Graphical Abstract

(a) Previous configuration (bioreactors in parallel)



(b) New configuration (bioreactors in series)



Keywords Mechanical–biological treatment · Biostabilized waste · Residual municipal solid waste

Statement of Novelty

This work presents a case study on the optimization of the aerobic treatment of a Mechanical–Biological Treatment (MBT) plant in Italy to account for the changes in feed waste composition related in particular to the increase in the separate collection of biowaste.

Introduction

Municipal solid waste (MSW) is characterized by significant amounts of organic biodegradable materials (biowaste) that may vary depending on the country's economy and waste management policies. Generally, the biowaste content of MSW tends to be higher in developing countries (up to 70%) than in developed countries, where it represents around 30–35% [1]. With regard to management strategies, the EU's waste policy has progressively promoted the decrease of landfilling and the implementation of measures to attenuate the impacts connected with waste disposal [2]. In particular, the disposal of biodegradable materials, which can entail methane production and the generation of polluted

leachate, needs to be minimized [3]. More recently, management approaches following the circular economy concept are being promoted in the EU also for biowaste fractions [4]. In particular, the separate collection of biodegradable organic fractions such as food and garden residues followed by specific treatments allows to convert this waste into compost employed as soil amendment, or into digestate used as fertilizer and to obtain biogas or biomethane to employ for electricity/heat generation or as a fuel, or into other valorizable products [4]. In cases in which separate collection of the biowaste fraction is still not widely or not effectively practiced, such as when separate collection is carried out prevalently through curbside collection, mechanical–biological treatment (MBT) represents a viable option for managing residual MSW [5]. In these cases, in fact, the resulting residual waste generally contains not only dry unrecoverable fractions, but also organic biodegradable matter and other items (e.g., metals) that may be recovered. These systems include two main treatment steps. Firstly, mechanical treatment (such as shredding, size, density and magnetic separation) aimed at recovering recyclable materials (e.g., metals and PET) and producing solid recovered fuel (SRF) from the mixed waste stream [6]. Secondly, biological stabilization of the biowaste contained in the MSW is applied to

reduce the weight and the biological activity of the degradable materials and thus their potential environmental impacts during landfilling [5, 7]. At the end of the whole process, the main outputs of an MBT plant are represented by SRF, biostabilized waste obtained from the biological stabilization process adopted in the plant (AB-SOW), ferrous and non-ferrous metals, and the scraps of the process that are landfilled [8–10].

The decision of adopting MBT for residual MSW management is mostly related to the need to comply with the targets of the European Directives concerning the banning of direct disposal of biodegradable waste [2; 11]. Many studies, in fact, showed the positive effects achieved by the adoption of the biostabilization treatment applied in MBT plants in terms of the improved production and quality of the leachate and biogas generated from landfilled stabilized biowaste [12–16]. On the other hand, SRF, which is characterized by a high calorific value related to its high content of paper and plastics, has attracted increasing interest as it can be employed as a fuel in combustion and co-combustion (including-waste to-energy) plants [8, 17–19].

It is well known that the characteristics of the MSW feeding the plant can significantly influence the quality and quantity of the outputs of an MBT plant [8, 9]. Over the last two decades, the characteristics of the inputs and outputs of the MBT plants and the environmental behavior of these materials in terms of both biogas emissions and leachate quality and quantity were extensively investigated. For instance, the physical–chemical properties (e.g., volatile solids, total and dissolved organic carbon, heavy metals content) and the biological characteristics (e.g., respiration activity) of the inputs and outputs of existing MBT plants were investigated by Münnich et al. [15], Rotter et al. [10], Bezama et al. [20], de Araújo Morais et al. [21], Lornage et al. [14] Montejo et al. [6], Bernat et al. [7], Di Maria et al. [12], Di Lonardo et al. [8], Trulli et al. [5], Fei et al. [19], Połomka et al. [22] and Tyagi et al. [23]. The biogas production of biologically treated municipal solid wastes was studied, for instance, by Ponsà et al. [24], van Praagh et al. [25], De Gioannis et al. [3], Scaglia et al. [16], Bayard et al. [26] and Pantini et al. [27]. The assessment of the leaching characteristics of MBT waste and the evaluation of the pre-treatment effects on the mobility of heavy metals and thus leachate emissions were instead investigated, for instance, by Robinson et al. [9], Siddiqui et al. [28, 29], Pantini et al. [30], Salati et al. [31], Lopez et al. [32] and Lieto et al. [33].

Based on the specific composition of the waste generated in different countries, the demand and role of MBT plants in MSW management can vary. For instance, in countries like China, where biowaste represents at least 50% of MSW, MBT is envisioned mainly as a pre-treatment for these fractions to improve landfill management [34]. In European countries, characterized by no or low separate collection

of biowaste fractions, both the stabilization of the biodegradable fractions and material/energy recovery are drivers for the installation of MBT plants. Around 180 MBT plants were installed from 1990 to 2010 [22]. Also, in the last decade, the treatment of the residual MSW by MBT has still been significantly applied [22]. It was estimated that in 2017 around 570 MBT plants were in operation in Europe, with a treatment capacity of 55 million tons, and other plants are envisioned to be installed by 2025 [35]. However, it is worth noting that recently the number of MBT plants installed yearly has somewhat decreased. As previously mentioned, in fact, the European Union is encouraging member states to adopt waste management policies based on the circular economy concept [36], entailing the need to increase material recovery and recycling by improving and optimizing separate collection of recoverable waste streams. In this framework, MBT should be seen hence as a transition technology. In fact, as separate collection increases in terms of both quantity and quality, MBT plants are no longer necessary, and the dry residual fraction can be sent directly to final disposal or waste to energy plants.

In Italy, the implementation of the separate collection of waste has increased significantly in the last two decades, with different trends observed region by region. Namely, in 2009 at the Italian national level, the percentage of separate collection was around 34%, with biowaste fractions accounting for 35% of the total collected materials [37]. In 2019, instead, the waste collected by source segregation resulted around 61%, with biowaste fractions accounting for 40% of the total waste [38]. Generally, higher percentages of source separate collection were observed in the north of Italy, whereas less efficient collection systems were found in the south. As far as waste management in the central regions of Italy, source separate collection passed from 25 to 58% from 2009 to 2019, with biowaste accounting for 29 and 39%, respectively [37, 38]. Notwithstanding the increase in separate collection, in central Italy, residual waste is still currently treated mainly in MBT plants. For example, in the city of Rome, around 2.2 million tons of MSW were generated in 2020 and separate collection was just over 50% (50.4%) [39]. The remaining residual waste is currently sent to three MBT plants, characterized by a total treatment capacity of around 2,250 tons/day.

As discussed previously, the increasing adoption in Italy of separate collection in the last two decades has strongly affected the composition of residual waste feeding MBT plants. Thus, the performances of existing MBT plants designed and optimized to treat waste presenting high percentages of biodegradable materials can be notably reduced. In this work, we present a case study of a full-scale and operational Italian MBT plant that showed a worsening of the performance of the biostabilization process after ten years of operation. The aim of the study was to identify and

test in the full-scale plant the effect of specific operating modifications to respond to the variations of MSW composition, in order to obtain a product that can meet biological stabilization requirements. To our knowledge, this aspect has not been specifically assessed in previous studies regarding MBT plants and the results may be relevant for contexts in which MBT is applied concurrently to the promotion of separate collection of biowaste fractions. In particular, the composition of the waste feeding the MBT plant and the biological stability degree of the output from the bioreactors of the plant were analyzed on representative samples. Furthermore, the operating parameters of the bioreactors in terms of airflow rate, the biogas temperature, the moisture content of the waste materials and temperature inside the bioreactor were determined weekly for eight weeks. Based on the results obtained in these investigations, a series of operating modifications to optimize the biostabilization process were implemented in the plant. Finally, a new monitoring campaign was carried out to evaluate the effects of the changes adopted.

Materials and Methods

MBT Plant

The MBT plant considered in this study is located in Rome and fed with residual mixed waste collected in some of the neighborhoods of the city of Rome and surrounding smaller municipalities. The biostabilized waste produced in this plant was examined in terms of its characteristics and maturation degree in different previous studies [8, 40–42]. This plant was installed in 2009 and was authorized for a maximum treatment capacity of 900 tons/day of MSW, considering an operativity of 312 days/year. The MBT plant is made up of a first treatment unit constituted by a bag breaking and size reduction process using hammer-mill shredders, after which the waste is fed into trommel screens for size separation (grate spacing of 65 mm). Two different flows are separated from this latter process: the dry (oversize) and the biodegradable (undersize) wet fraction. The dry fraction is characterized by lower moisture and is typically made up by materials with a high heating value and is used for producing SRF. Namely, the produced solid refuse fuel, according to the Italian technical standard UNI EN 15359 [43], can be classified as class 3 for the mean net calorific value (i.e. ≥ 15 MJ/kg as received), as class 2 or 3 for the chlorine content (i.e. ≤ 0.6 or $\leq 1\%$ wt) and as class 1 for the mean mercury content (i.e. ≤ 0.02 mg/MJ as received). This SRF is currently sent to waste to energy plants, although, based on these characteristics, it could also be employed as fuel in cement kilns and other combustion and co-combustion plants. The biodegradable fraction, instead, presents higher

moisture and percentage of organic compounds. After the metals' removal (performed by belt-type electromagnetic separators), the biodegradable fraction is sent to two stabilization bioreactors operating in parallel. Each bioreactor presents a volume of 6,700 m³ and allows to carry out aerobic biodegradation at forced aerated conditions for four weeks. The stabilized output is then screened in a refining unit (20 mm) to separate the stabilized waste from scraps and inert materials. A schematic layout of the MBT plant employed as case study in this paper is reported in Fig. 1.

Monitoring and Optimization of the Operating Parameters

In order to assess the performance of the biodegradation process adopted in the MBT plant, both the composition of the feed residual MSW and the characteristics of the output biostabilized waste in terms of volatile solids (VS) content and biological stability degree were evaluated.

During 2019 and 2020, two monitoring campaigns were performed on the two stabilization bioreactors of the plant (Fig. 2). For each bioreactor the air flow rate, the temperature of the biogas, the humidity of the waste samples, the temperature inside the bioreactor and the DRI value were weekly measured for 8 weeks. Namely, the air flow rate and the temperature of the biogas were measured placing specific probes in each of the four suction pipes present in the bioreactor and recording the 1 h-average value. The temperature of the wastes inside each bioreactor was measured selecting 16 representative points in the waste body and inserting the probe at a depth of 1.5 m whereas the waste humidity was determined collecting in the same areas 16 samples of approximately 1 kg of waste. The DRI values were measured on the waste exiting from the bioreactor by collecting three 12 kg-samples. Hence, in each 8 weeks-monitoring campaign carried out in 2019 and 2020 for each bioreactor 32 measurements for the air flowrate and the temperature of the biogas, 144 measurements for the temperature and humidity of the waste and 24 measurements of the biological stabilization degree were totally collected (see Table 1 and Table 3).

Analytical Methods

The composition of the residual mixed waste fed to the plant was evaluated based on 3 samples, each weighing approximately 100–200 kg, by manually separating ten different fractions, in accordance with the APAT method [44].

The airflow rate was measured using a multi-parametric analyzer (Testo 400) equipped with a Pitot Tube probe (Testo 0635-2140 Probe Pitot Tube). The temperature in the biogas lines of the aerobic bioreactors was measured using the same multi-parametric analyzer (Testo 400) but equipped with a NTC-type temperature probe (Testo 0615-5605). The

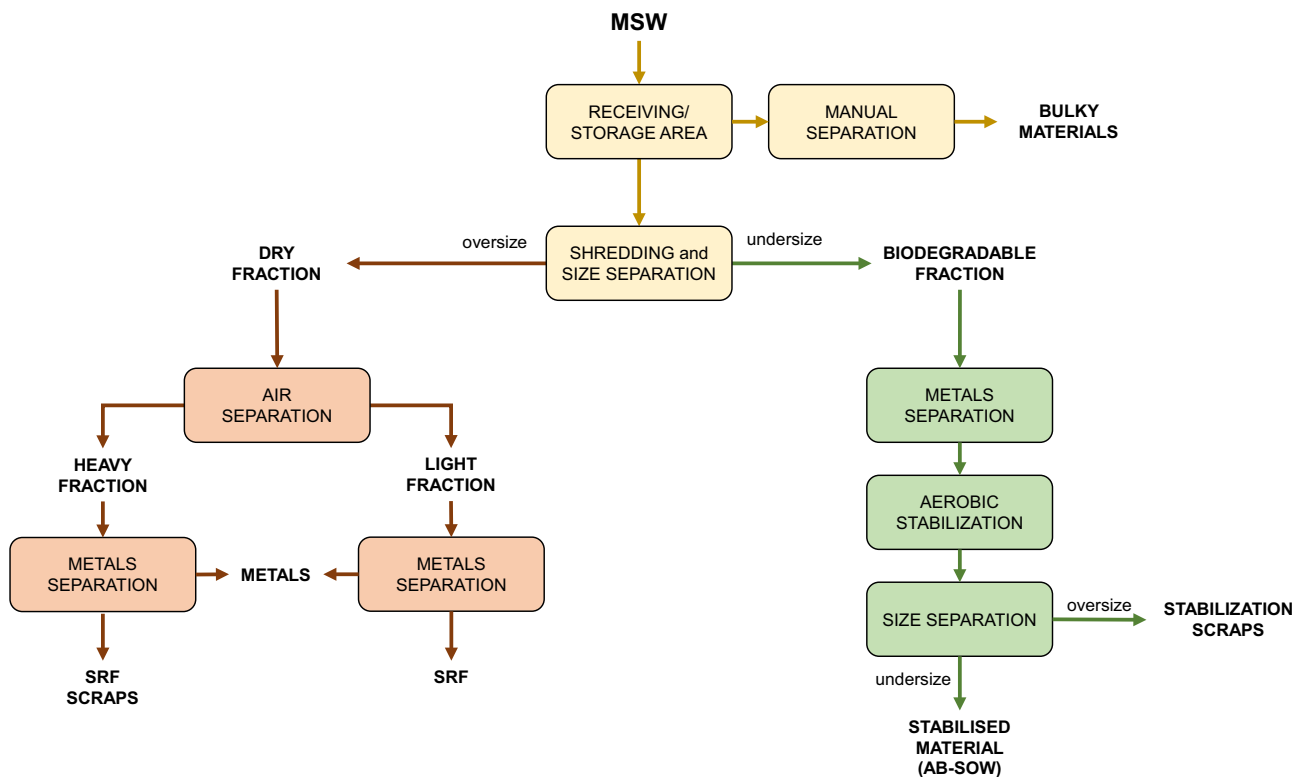


Fig. 1 Schematic layout of the MBT plant



Fig. 2 Aerobic bioreactors in the studied MBT plant

temperature in the waste materials inside the aerobic bioreactors was measured with a NTC portable thermometer (Testo 110) equipped with a NTC-type temperature probe (Testo 0613-1212). The moisture content of the waste materials inside the aerobic bioreactors was determined according to the UNI-EN 15934:2012 method [45].

The biological stability degree was analyzed by determining the potential DRI of the sample, which provides information about the absolute maximum rate of oxygen consumption due to microbial activity [44]. DRI was measured on 12 kg-samples of biostabilized waste by means of an adiabatic respirometer (Costech International Respirometer

Table 1 Processing control parameters in the two bioreactors detected in 2019

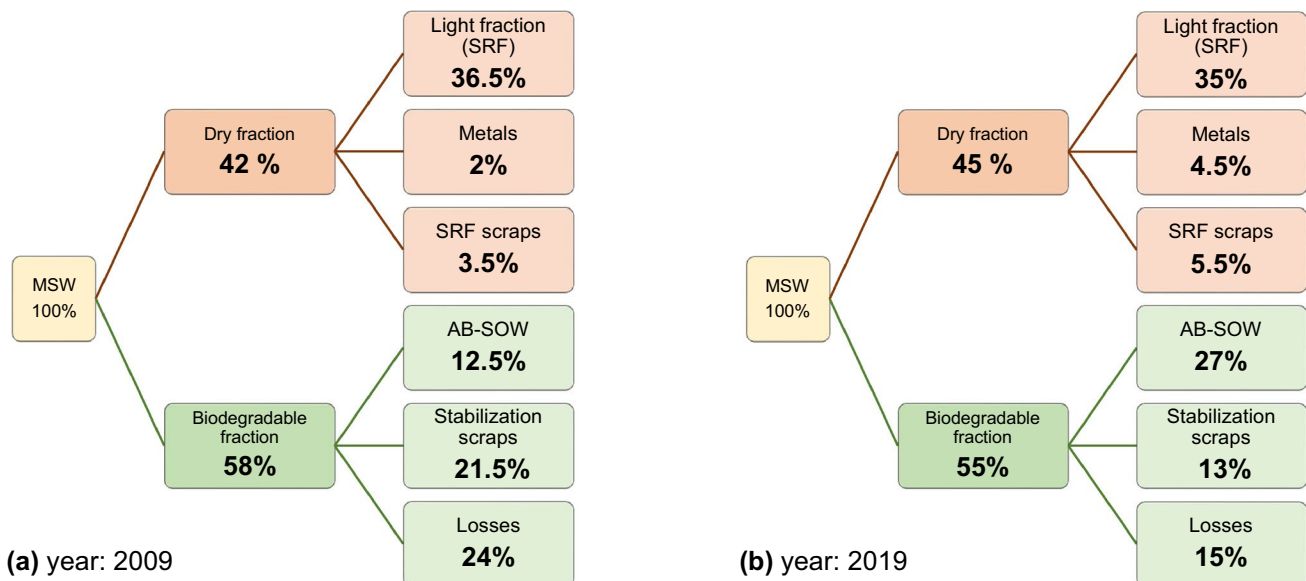
Parameter	Units	Replicates	Mean	St.Dev	CV (St.Dev/ Mean) (%)	Min	Max
<i>Bioreactor 1</i>							
Airflow rate	m ³ /h	32 (4 for 8 weeks)	18,016	502	2.8	17,120	18,620
Temperature of biogas	°C	32 (4 for 8 weeks)	61	3	5	56	67
Temperature of waste materials	°C	144 (16 for 8 weeks)	65	4	7	57	70
Humidity of waste materials	%	144 (16 for 8 weeks)	34	3	8	29	41
Dynamic Respiration Index (DRI)	mg _{O₂} /kg _{VS} /h	24 (3 for 8 weeks)	3666	185	5	3381	3935
<i>Bioreactor 2</i>							
Airflow rate	m ³ /h	32 (4 for 8 weeks)	13,233	535	4.0	12,730	14,120
Temperature of biogas	°C	32 (4 for 8 weeks)	63	5	7	55	69
Temperature of waste materials	°C	144 (16 for 8 weeks)	65	3	5	60	70
Humidity of waste materials	%	144 (16 for 8 weeks)	34	2	6	30	37
Dynamic Respiration Index (DRI)	mg _{O₂} /kg _{VS} /h	24 (3 for 8 weeks)	4184	183	4	3959	4521

3024), according to the procedure reported in the Italian Standard UNI/TS 11184-Method A (2016) [46]. In order to estimate the DRI value, the volatile solids (VS) content was determined on 50 g of the same waste sample by measuring the loss-on-ignition after 6 h at 550 °C according to UNI/TS 11,184 [46].

Results and Discussion

Changes in the Composition of the Feed MSW to the MBT Plant from 2009 to 2019

The mass balance of the municipal solid waste (MSW) fed to the MBT plant at the start-up (2009) and in 2019 is shown in Fig. 3. It can be observed that starting from the same authorized mass capacity (900 tons/day), after approximately ten years of operation, there was a slight change in the distribution of the waste at the primary sieve that dimensionally separates the light fraction (i.e., dry fraction) from the smaller one sent to aerobic stabilization (i.e., biodegradable

**Fig. 3** Mass balance at the start-up of the MBT plant in 2009 (a) and in 2019 (b)

fraction). For these flows, in 2019, compared to the start-up in 2009, there was a reduction of the biodegradable fraction from about 58% to less than 55% and consequently a slight increase in the light fractions (from about 42% to less than 45%). More significant changes were instead observed in the output mass flow distribution from the stabilization bioreactors. In this case, it can be observed that the biostabilized scraps decreased from 21.5% (in 2009) to 13% (in 2019), while the aerobically biostabilized organic waste (AB-SOW) increased from 12.5% at the start-up to 27% in 2019.

The composition of the input MSW treated in the MBT plant at the start-up in 2009 and in 2019 is shown in Fig. 4. It can be observed that also in this case, relevant changes were detected. Specifically, it can be noticed that the biowaste fractions (in terms of organic waste—OW—and fine materials < 20 mm—F) were significantly lower in 2019 compared to the start-up of the plant, from about 29% (18.7% for OW and 10.1% for F) to 11% (7% for OW and 4% for F). Conversely, the percentages of paper-cardboard and plastics considerably increased after ten years, varying from about 31% for paper-cardboard and 22% for plastics to about 35% and 40%, respectively.

These changes can be attributed to the progressive modification of waste management strategies adopted in Rome in terms of separate collection of MSW. As already discussed earlier, in the center of Italy, the percentage of source segregated collection more than doubled from 2009 to 2019, with that of biowaste waste increasing from 29 to 39%, thus entailing a reduction of the content of the biowaste fraction of residual MSW fed to the MBT plant.

These changes were also reflected in the stability of the biowaste fraction after aerobic stabilization (AB-SOW).

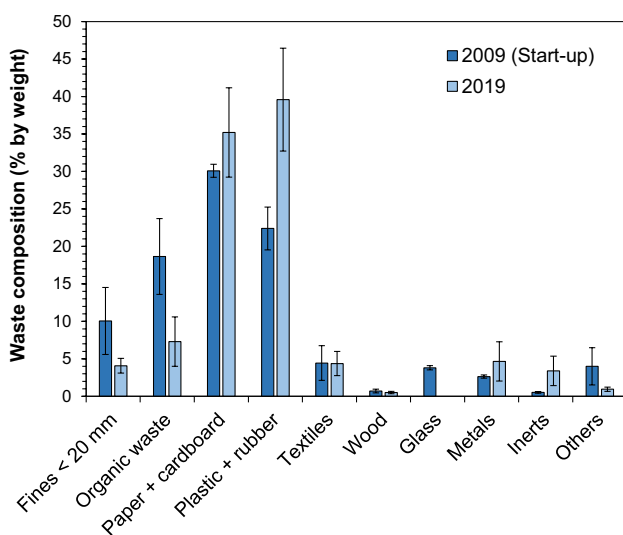


Fig. 4 MSW composition treated in the MBT plant. Comparison between the start-up (2009) and the year 2019

Indeed, while at the start-up, the Dynamic Respiration Index (DRI) was below the limit value of 1,000 mg_{O₂}/kg_{VS}/h, in 2019 significantly higher DRI values, in the order of 3000–4000 mg_{O₂}/kg_{VS}/h, were detected (see next section).

Investigations Carried Out in 2019

At the beginning of 2019, the composition of the fractions obtained by the primary separator (grate spacing of 65 mm) of the MBT plant was first analyzed. The composition of the dry (oversize) and the biodegradable (undersize) fraction are shown in Fig. 5a. These investigations highlighted that the biodegradable fraction was characterized by a significant fraction of paper (around 47%) and plastic (about 26%) materials (see Fig. 5a) that surely affected the overall biodegradability of the waste feeding the aerobic bioreactors. Namely, the high content of paper and plastic materials could be the main cause of non-compliance with the limits established for the DRI. The high content of paper and plastic materials also explains the size distribution of the MSW treated at the MBT plant that, as shown in Fig. 5b, resulted higher than 50 mm for around 85% of the analyzed waste.

Furthermore, during 2019, the main control parameters of the aerobic stabilization process carried out in the two bioreactors (Bioreactor 1 and Bioreactor 2) of the MBT plant operating in parallel (see Fig. 6a) were also determined weekly. The investigated parameters in each bioreactor were the humidity of the waste materials, the biogas temperature, the temperature of the materials inside the bioreactors, the airflow rate, and the DRI. The obtained results in terms of average values, standard deviation, coefficient of variation (CV) and range (min–max) of the samples analyzed in each bioreactor are reported in Table 1.

From this table, it can be first observed that in both bioreactors, as discussed earlier, the DRI value resulted higher than the limit value of 1000 mg_{O₂}/kg_{VS}/h with an average value of 3666 mg_{O₂}/kg_{VS}/h in Bioreactor 1 and 4,184 mg_{O₂}/kg_{VS}/h in Bioreactor 2.

In terms of controlling parameters for the biostabilization process, it can be observed that the average temperature inside the material and in the biogas was in the order of 61–65 °C in both bioreactors. These values are not far from the optimum values suggested for composting. For instance, MacGregor et al. [47] found that optimum composting temperatures for maximizing decomposition were in the range of 52–60 °C. It is indeed widely accepted that temperature plays a crucial role in composting efficiency as microbial metabolism is highly temperature-dependent, but also the composition and density of microbes are dramatically influenced by temperature [48]. For instance, temperatures below 20 °C can slow or even stop the composting process, while for temperatures significantly higher than 60 °C microbial

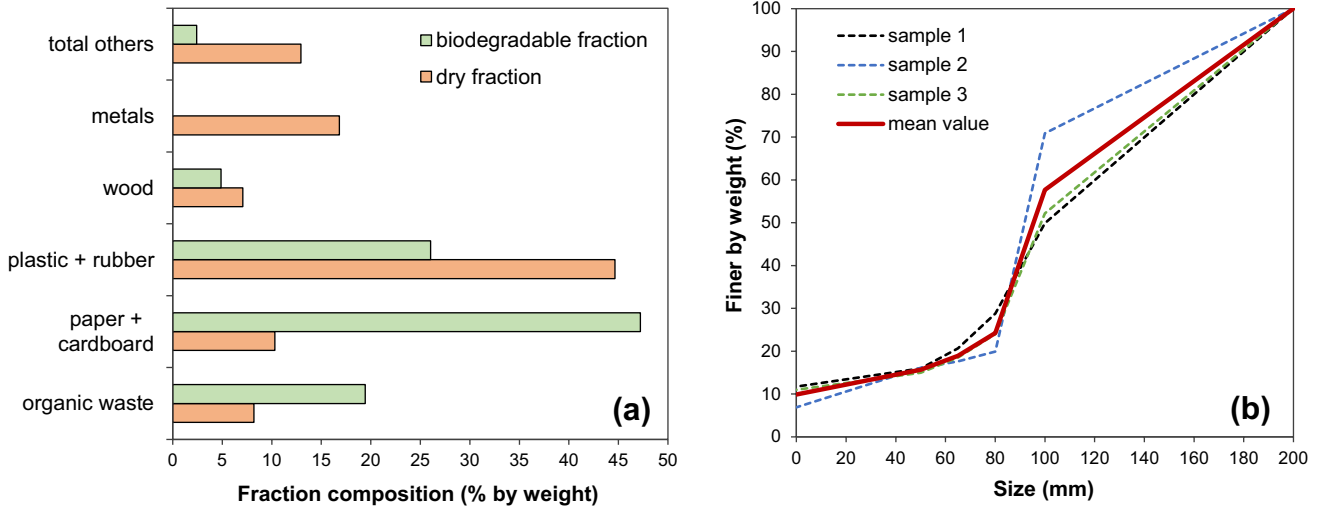


Fig. 5 Composition of the overflow (dry fraction) and under flow (biodegradable fraction) obtained by the primary separator (65 mm) of the MBT plant (a) and size distribution of the 3 samples (and mean

value) of MSW collected in the MBT plant before the primary separator (b). These analysis are referred to the year 2019

(a) Previous configuration (bioreactors in parallel)

(b) New configuration (bioreactors in series)

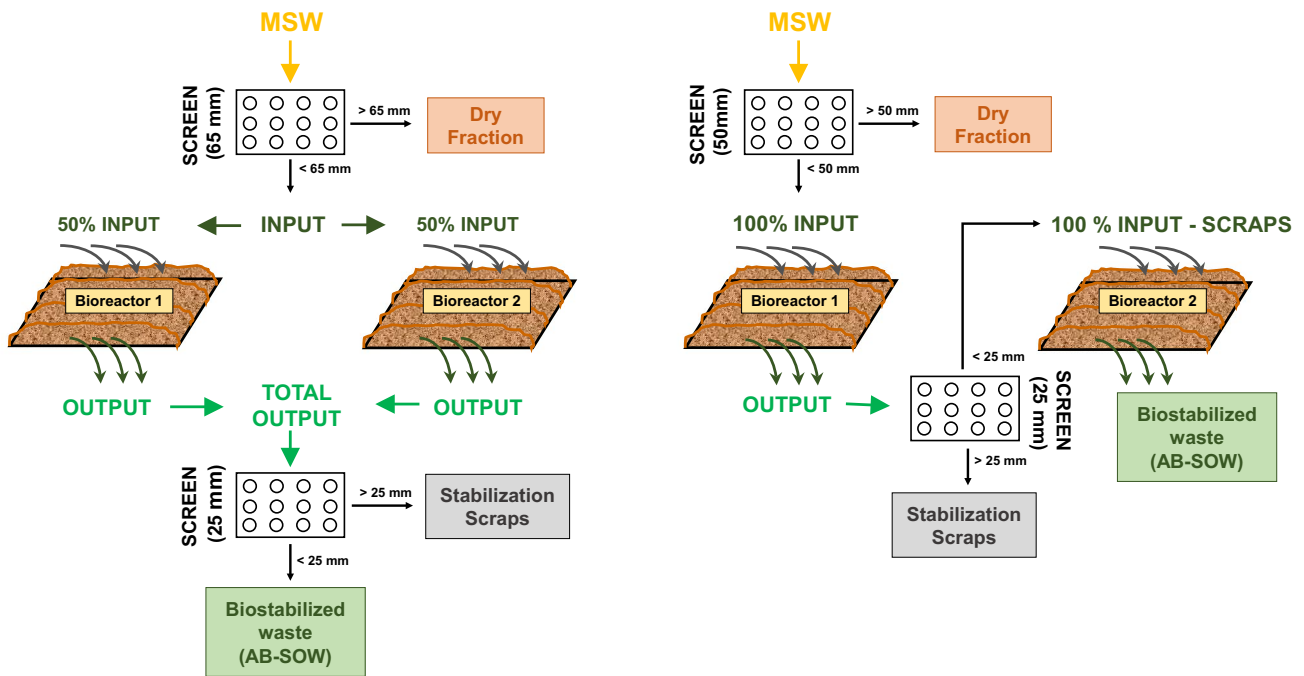


Fig. 6 a Previous and b new configuration of the aerobic stabilization treatment in the MBT plant

activity declines as the thermophilic conditions for microorganisms are surpassed [49].

As for the moisture content, the average values in the bioreactors were in the order of 34% (see Table 1). According to the literature, these values are lower than the optimal conditions for aerobic stabilization. Many researchers,

indeed, found that moisture content of 50–60% is suitable for efficient composting [50–52].

In terms of airflow rates, the average values for the two bioreactors were in the order of approximately 18,000 m³/h for Bioreactor 1 and 13,000 m³/h for Bioreactor 2. Considering that each bioreactor has a volume of about 6,700 m³, the

total waste inside each bioreactor can be up to 3,900 tons (assuming a specific weight for the biodegradable fraction of 580 kg/m^3). Thus, normalizing the airflow rates detected in 2019 to the total amount of waste present in each bioreactor, the aeration rates were in the order of $0.08 L_{\text{air}}/(\text{min} \times \text{kg}_{\text{OM}})$ for Bioreactor 1 and $0.06 L_{\text{air}}/(\text{min} \times \text{kg}_{\text{OM}})$ for Bioreactor 2. These values are lower than the values applied by other researchers that were in the range of 0.3 to $1.16 L_{\text{air}}/(\text{min} \times \text{kg}_{\text{OM}})$ [53–55]. It is, however, worth mentioning that the aeration rates calculated for the two bioreactors refer only to forced aeration without considering the further contribution resulting from the physical turning of the waste mass that in each bioreactor is carried out daily.

Optimization of the Process

Based on the values detected in the two bioreactors, the first optimization proposed consisted of increasing the water and air flows to be supplied in each bioreactor.

Furthermore, considering the reduced content of the bio-waste fractions found in the composition analysis of the feed MSW, the attention was focused on management operations aimed at reducing the content of paper and plastic materials in the aerobic bioreactors. Thus, it was proposed to modify the primary separator by adopting circular holes of 50 mm in place of the 65 mm screen previously applied.

As shown in Fig. 6, this modification can have significant beneficial effects considering that more than 85% of the waste upstream of the shredder had dimensions greater than 50 mm. In addition, to optimize the biological process, it was proposed to use the two bioreactors in series (in place of the previous configuration with the bioreactors in parallel) implementing a mechanical separation (with 25 mm screens) from the first (Bioreactor 1) to the second (Bioreactor 2) unit (see Fig. 6).

This new configuration can indeed lead to a decrease in the volumes of material daily fed to the second bioreactor, thus increasing the residence time and the possibility of achieving a better degree of biostabilization of the waste. Namely, as shown in Table 2, with this new configuration, the residence time can be increased by around 20% from approximately 16 days, using the bioreactors in parallel, to around 19 days with the configuration of the bioreactors operating in series. Specifically, considering that the maximum waste capacity of the plant is 900 tons/day and the biodegradable fraction in 2019 was around 55% (see Fig. 3b), the waste feeding the two stabilization bioreactors were about 495 tons/day (i.e., around 247.5 tons/day in each bioreactor operating in parallel). By assuming a specific weight of the biodegradable fraction of 580 kg/m^3 , the waste daily fed to the stabilization process was around $853 \text{ m}^3/\text{day}$, i.e., $427 \text{ m}^3/\text{day}$ for each bioreactor. Considering

Table 2 Residence time using the bioreactors in parallel or in series (2019)

Parameter	Units	Value
<i>General parameters</i>		
Maximum waste capacity of the plant (Q)	tons/day	900
Volume of each stabilization basin (V)	m^3	6700
Biodegradable fraction in 2019 compared to total capacity (f_b)	%	55%
Scraps fraction in 2019 compared to total capacity (f_s)	%	13%
Daily biodegradable materials feeding the reactors ($Q_b = Q \times f_b$)	tons/day	495
Daily scraps materials from the reactors ($Q_s = Q \times f_s$)	tons/day	117
<i>Stabilization basins (Bioreactor 1 and Bioreactor 2) operating in parallel</i>		
Mass of biodegradable materials daily feeding each unit ($Q_{1/2}$)	tons/day	247.5
Specific weight of the biodegradable fraction feeding Bioreactor 1 and Bioreactor 2 (γ_b)	kg/m^3	580
Volume of biodegradable materials daily feeding the two units ($V_{1/2} = Q_{1/2} \times 1000 / \gamma_b$)	m^3/day	427
Residence time in Bioreactor 1 and Bioreactor 2 ($t_R = V / V_{1/2}$)	days	16
<i>Stabilization basins (Bioreactor 1 and Bioreactor 2) operating in series</i>		
Mass of biodegradable materials daily feeding Bioreactor 1 (Q_1)	tons/day	495
Specific weight of the biodegradable fraction feeding Bioreactor 1 (γ_b)	kg/m^3	580
Volume of materials daily feeding Bioreactor 1 ($V_1 = Q_1 \times 1000 / \gamma_b$)	m^3/day	853
Residence time in Bioreactor 1 ($t_{R1} = V / V_1$)	days	8
Daily scraps removed after Bioreactor 1 (Q_s)	tons/day	117
Mass of materials daily feeding Bioreactor 2 ($Q_2 = Q_1 - Q_s$)	tons/day	378
Specific weight of the refined biodegradable fraction in Bioreactor 2 (γ_{br})	kg/m^3	640
Volume of biodegradable materials daily feeding Bioreactor 2 ($V_2 = Q_2 \times 1000 / \gamma_{br}$)	m^3/day	591
Residence time in Bioreactor 2 ($t_{R2} = V / V_2$)	days	11
Total residence time ($t_R = t_{R1} + t_{R2}$)	days	19

that each bioreactor has a volume of 6700 m³, the residence time in each bioreactor (assuming a configuration in parallel) was in the order of 16 days. In the configuration in series, instead, in Bioreactor 1 assuming the same biodegradation fraction and the same specific weight (i.e., 55% and 580 kg/m³, respectively), the waste feeding the first bioreactor can be assumed equal to 495 tons/day (equal to 853 m³/day) with a corresponding residence time of 8 days. By employing mechanical separation before Bioreactor 2, around 117 tons/day can be discarded (i.e., 13% of the total waste, see Table 2). In this way, the waste feeding the second bioreactor is in the order of 378 tons/day. Considering a specific weight of the output refined biodegradable materials from Bioreactor 1 of 640 kg/m³, the daily volume of waste feeding the second bioreactor is 591 m³/day with a consequent residence time in Bioreactor 2 of 11 days. Thus, in the configuration in series, the overall residence time of waste materials is 19 days. Note that in this estimate, the further refinement proposed for the primary separator (i.e., the adoption of circular holes of 50 mm in place of the 65 mm screen previously applied) was not considered. This option can further reduce the amount of waste feeding the two bioreactors, thus increasing the residence time of waste materials undergoing biostabilization.

Starting from the second half of 2019, the operational modifications of the system discussed in the previous section were adopted. Namely, the air and water supply were optimized, a configuration in series was adopted for the two bioreactors and a smaller screen of 50 mm instead of 65 mm in the primary separator was employed. After these changes, the process was gradually started up and optimized to the modified configuration until the process stability was reached in the summer of 2020. Furthermore, in 2020 the same investigations carried out in 2019 in terms of the water content of the samples, the temperature of the biogas, temperature in the bioreactor, airflow rate and DRI value were

repeated. The obtained results are reported in Table 3 in terms of average values, standard deviation, coefficient of variation (CV) and range (min–max) of the values observed in each bioreactor.

The mass balance of the different fractions in the MBT plant after implementing the modifications discussed above is shown in Fig. 7. As can be seen, the adoption of a smaller screen in the primary separator led to a reduction in the bio-waste fraction from 55% (in 2019) to 40% (in 2020), with a consequent increase in the dry fraction, especially in terms of SRF (47% in 2020 instead of 35% in 2019).

The new configuration for the air and water supply allowed to achieve an average airflow rate in the two

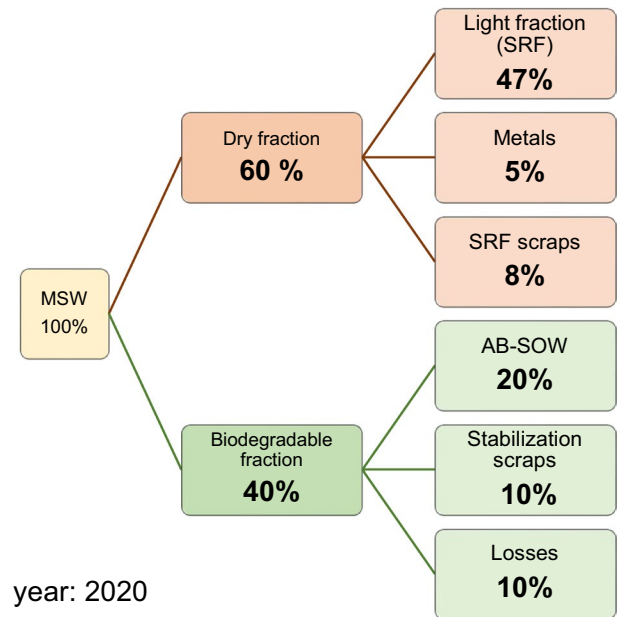


Fig. 7 Mass balance of the different fractions in 2020 after the process optimization

Table 3 Processing control parameters in the two bioreactors detected in 2020

Bioreactor 1							
Parameter	Units	Replicates	Mean	St.Dev	CV (St.Dev/Mean)	Min	Max
Airflow rate	m ³ /h	32 (4 for 8 weeks)	25,906	2376	9.2%	20,030	26,880
Temperature of biogas	°C	32 (4 for 8 weeks)	59.8	3.1	5.1%	55.0	66.0
Temperature of waste materials	°C	144 (16 for 8 weeks)	71.0	3.1	4.4%	63.0	80.0
Humidity of waste materials	%	144 (16 for 8 weeks)	37.1	6.1	16.4%	25.2	47.0
Bioreactor 2							
Airflow rate	m ³ /h	32 (4 for 8 weeks)	18,118	148	0.8%	17,980	18,350
Temperature of biogas	°C	32 (4 for 8 weeks)	49	12	25%	26	60
Temperature of waste materials	°C	144 (16 for 8 weeks)	72	4	6%	64	79
Humidity of waste materials	%	144 (16 for 8 weeks)	38	4	11%	30	45
Dynamic Respiration Index (DRI)	mg _{O2} /kg _{Vs} /h	24 (3 for 8 weeks)	901	53	6%	849	1002

bioreactors of 40% higher than in the previous configuration, while the moisture content was around 10% higher in both bioreactors. Specifically, the waste materials' average moisture content detected in 2020 was around 37–38% against an average value of 34% in 2019. The average values of the airflow rate in 2020 for the two bioreactors were in the order of approximately 26,000 m³/h for Bioreactor 1 and 18,000 m³/h for Bioreactor 2. Considering that each bioreactor has a volume of approximately 6,700 m³, the total waste inside Bioreactor 1 can be up to 3,900 tons (assuming a specific weight for the biodegradable fraction of 580 kg/m³) and up to 4,300 tons inside Bioreactor 2 (assuming a specific weight for the biodegradable fraction of 640 kg/m³). Thus, normalizing the airflow rates detected in 2020 to the total amount of waste present in each bioreactor, the aeration rates were in the order of 0.11 L_{air}/(min × kg_{OM}) for Bioreactor 1 and 0.07 L_{air}/(min × kg_{OM}) for Bioreactor 2, thus higher than the ones applied in 2019 that as discussed earlier were in the order of 0.08 L_{air}/(min × kg_{OM}) for Bioreactor 1 and 0.06 L_{air}/(min × kg_{OM}) for Bioreactor 2.

Furthermore, with the adoption of the new configuration in series, the residence time calculated following the procedure discussed earlier resulted in the order of 27 days (see Table 4). This value is higher than the 19 days estimated assuming a configuration in series with the data of 2019 (Table 2) since, as discussed above, the adoption of a smaller screen in the primary separator exerted a reduction of the materials daily feeding the aerobic bioreactors from 495 tons/day in 2019 to 360 tons/day in 2020 (see Table 2 and Table 4 respectively). All three modifications adopted in the MBT plant contributed in increasing the stability of

the materials. Indeed, differently from what was observed in 2019, the stabilization degree of the output material measured in 2020 showed to comply with the established limit of 1000 mgO₂/kg_{V_S}/h.

Conclusions

The results of the case study presented in this work showed that the variation of the composition of the MSW feeding MBT plants, such as that which occurred in the city of Rome during the examined period, can alter the performance of the plant. Specifically, in the considered case study, a worsening of the biological stability degree of the output waste of the plant was observed after ten years of operation (2009–2019), with average DRI values detected in 2019 of around 4000 mgO₂/kg_{V_S}/h.

The analyses carried out on the composition of the waste feeding the bioreactors of the plant showed that the treated waste materials presented a significantly higher content of plastic and paper materials (around 75%) compared to at the start-up of the plant (55%). This variation in the waste composition was related to the increasing adoption in the last decade of separate collection of several fractions, including biowaste from MSW in the city of Rome. The higher content of plastic and paper materials was identified as the main cause of the worsening of the performance of the biostabilization process of the MBT plant. High contents of plastics and paper materials in the bioreactors can cause a slowing down of the degradation kinetics, leading to incomplete biological degradation of the organic matter.

Table 4 Assessment of the residence time expected using the bioreactors in series (2020)

Parameter	Units	Value
<i>General parameters</i>		
Maximum waste capacity of the plant (Q)	tons/day	900
Volume of each stabilization basin (V)	m ³	6700
Biodegradable fraction in 2020 (f _b) compared to total capacity	%	40%
Scraps fraction in 2020 (f _s) compared to total capacity	%	13%
Daily biodegradable materials feeding the reactors (Q _b = Q × f _b)	tons/day	360
Daily scraps materials from the reactors (Q _s = Q × f _s)	tons/day	117
<i>Stabilization basins (Bioreactor 1 and Bioreactor 2) operating in series</i>		
Mass of biodegradable materials daily feeding Bioreactor 1 (Q ₁)	tons/day	360
Specific weight of the biodegradable fraction feeding Bioreactor 1 (γ _b)	kg/m ³	580
Volume of materials daily feeding Bioreactor 1 (V ₁ = Q ₁ × 1000 / γ _b)	m ³ /day	621
Residence time in Bioreactor 1 (t _{R1} = V / V ₁)	days	11
Daily scraps removed after Bioreactor 1 (Q _s)	tons/day	90
Mass of materials daily feeding Bioreactor 2 (Q ₂ = Q ₁ − Q _s)	tons/day	270
Specific weight of the refined biodegradable fraction in Bioreactor 2 (γ _{br})	kg/m ³	640
Volume of biodegradable materials daily feeding Bioreactor 2 (V ₂ = Q ₂ × 1000 / γ _{br})	m ³ /day	422
Residence time in Bioreactor 2 (t _{R2} = V / V ₂)	days	16
Total residence time (t _R = t _{R1} + t _{R2})	days	27

On the other hand, the analysis carried out weekly for eight weeks on the bioreactors showed that the airflow rates and the moisture content inside the bioreactors were below the optimal values suggested in the literature to ensure an effective biostabilization process.

To restore the functionality of the biostabilization process, the following modifications were employed in the plant:

- Reduction of the mesh size of the primary mechanical separator from 65 to 50 mm circular holes mesh. In this way, a reduction of the waste materials sent to the two bioreactors of the MBT plant from 55% (in 2019) to 40% (in 2020) with a consequent increase in the dry fraction, especially in terms of SRF (47% in 2020 instead of 35% in 2019) was obtained.
- The bioreactor configuration was changed by placing the two bioreactors in series in place of the previous configuration in parallel and by installing a screening unit (25 mm) before transferring the material from Bioreactor 1 to Bioreactor 2. In this way, after a primary aerobic biostabilization step in the first bioreactor, the larger scraps are separated from the materials sent to the second bioreactor. These changes allowed to increase of around 70% the residence time of the waste materials inside the bioreactors, achieving an aerobic treatment time of 27 days with the new configuration compared to the 16 days obtained with the previous configuration.
- Enhancement of the airflow rates and the moisture content of waste materials inside the bioreactors of around 40% and 10%, respectively. In this way, it was possible to enhance the performance of the biostabilization process.
- The investigation carried out in 2020 showed that the implementation of these modifications had beneficial environmental and economic effects. From an environmental point of view, a reduction of the biodegradable fraction leaving the plant from 55% in 2019 to 40% in 2020 was obtaining, leading to a reduction in the amount of waste sent to landfilling. Furthermore, after the implementation of the changes described above, the biostabilized materials presented a stability degree below the established limit of 1000 mg_{O₂}/kg_{V_S}/h. On the other hand, the increase of dry fraction from 45% in 2019 to 60% in 2020 can represent a potential economic benefit as the SRF fraction can potentially be used as fuel in combustion and co-combustion plants.

It is anyhow worth mentioning that owing to the transitional role of MBT in waste treatment strategies, when separate collection of biowaste will be optimized, these types of treatment solutions will no longer be necessary. In this future configuration, the plants could be modified in order to be employed to further separate individually collected flows

such as plastics and metals, whereas the bioreactors could be modified to receive the source separated organic materials that could be treated for compost production.

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Data Availability Enquiries about data availability should be directed to the authors

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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