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Analysis of MSW full-scale facilities based on anaerobic digestion and/or composting using respiration indices as performance indicators

J. Colón[a], S. Ponsá[a], C. Álvarez[b], M. Vinot[b], F.J. Lafuente[a], D. Gabriel[a] and A. Sánchez[a,*]

[a] Department of Chemical, Biological and Environmental Engineering
Escola d'Enginyeria
Universitat Autònoma de Barcelona, 08193 Barcelona, Spain
[b] R+D+i Department, URBASER S.A., 28031 Madrid, Spain

* Corresponding author:

Dr. Antoni Sánchez

Email address: antoni.sanchez@uab.cat

Abstract

The Landfill Directive (1999/31/EC) forces European States to reduce the amount of biodegradable municipal waste landfilled to 35% of 1995 levels. Mechanical-Biological Treatment (MBT) plants are the main alternative to waste incineration and landfilling. In this work, the waste treatment efficiency of six full-scale MBT facilities has been analysed using respiration indices (Dynamic Respiration Index and Cumulative Oxygen Consumption) to monitor plant performance. MBTs relying on anaerobic digestion plus composting achieved a high grade of stability on final compost (0.24 ± 0.09 mg O_2 g^{-1}DM h^{-1} and 20 ± 9 mg O_2 g^{-1}DM for dynamic respiration and cumulative consumption, respectively). On the contrary, MBTs relying only on composting showed a poor performance (1.3 ± 0.2 mg O_2 g^{-1}DM h^{-1} and 104 ± 18 mg O_2 g^{-1}DM for dynamic respiration and cumulative consumption, respectively). These results highlight the usefulness of respirometric balances to assess the performance of MBT full-scale plants.

Keywords: MBT, Composting, Anaerobic Digestion, Dynamic Respiration Index, Cumulative Respiration Index.

1. Introduction

The European Union (EU) approach to waste management is based on three principles: waste prevention, recycling and reuse, and improving final disposal and monitoring. Based on these principles, EU published the Landfill Directive 1999/31/EC in 1999 (European Commission 1999) and the Waste Framework Directive 2008/98/EC in 2008 (European Commission 2008), which especially restricts landfilling of biodegradable waste and forces the pre-treatment of municipal wastes.

The Landfill Directive enforces Member States to reduce by 2016 (2020 for some countries) the amount of biodegradable municipal waste (composed mainly by 60 % of food and green waste, and by 40 % of paper and cardboard) landfilled to 35% of 1995 levels . As an indication, the EU-15 State Members produced 109 million tons of biodegradable municipal wastes in 1995 (European Commission 2004) while the EU-27 produced in 2010 about 2500 million tons of waste from which household waste contributed up to 219 million tons (8.7 %) (Eurostat 2014).

Mechanical-Biological Treatment plants (MBT) are currently the main alternative to waste incineration and to avoid landfilling of untreated biodegradable wastes. Approximately two-thirds of biodegradable municipal waste produced in the EU were landfilled in 2004, which was a potential barrier to meet the landfill diversion targets throughout the EU (European Commission 2004). Since then, biological treatment capacity has substantially increased. The number of MBT plants in operation at the end of 2011 was about 330, which corresponded to a treatment capacity of about 34 million tons of MSW (EcoProg 2011). The number of MBT in operation increased up to 60 % from 2005 to 2011 while treatment capacities grew by about 70 % within the same period. This growth is expected to continue. By the end of 2016, the installed treatment capacity in Europe is predicted to be close to 46 million tons per year (EcoProg 2011).

A MBT plant is a type of waste processing facility that combines a sorting facility with a biological treatment such as composting and/or anaerobic digestion. MBT plants relying on composting are widely spread all over Europe, even if the treatment capacity of plants that combine anaerobic and aerobic treatments is rapidly increasing. The latter type of facilities has grown from 3 in 1990 to more than 170 plants installed by the end of 2010 with a digestion capacity of more than 5 million tons per year, which corresponded approximately to 20 % of the biological treatment capacity for organics derived from household waste during 2010 (De Baere and Mattheeuws, 2008). MBT plants are mainly designed to process mixed municipal solid waste (MSW) but also source-selected organic fraction of municipal solid waste (OFMSW). Within this general classification, multiple variations can be found and it can be stated that probably there are no two identical plants, although some configurations are quite similar. MBT includes a wide range of different technologies and defining an average facility is therefore difficult.

The analysis of waste treatment efficiency in these plants requires a reliable measure of the biodegradable organic matter content of organic wastes and thus, their stability defined as the extent to which readily biodegradable organic matter has decomposed (Lasaridi and Stentiford 1998). In this field, the application of respiration indices (RI) is widely accepted in both scientific literature and European legislations (European Commission 2001; US Department of Agriculture 2001; Adani et al. 2006; Gomez et al. 2006; European Committee for Standardization 2007; Ponsá et al. 2010a). Among all available respirometric techniques, several European countries have adopted the indices proposed by the European Commission in its 2nd draft of the *Working Document on Biological Treatment of Biowaste* (European Commission 2001). This regulation proposes two dynamic respirometric methods: (i) the Dynamic Respirometric Index

(DRI) and (ii) the Cumulated Oxygen Consumption at 4 days (AT_4). These indices had proven to be very useful for monitoring the performance of a wide variety of full-scale waste treatment facilities (Ponsá et al. 2008; Ponsá et al. 2010b; Pognani et al. 2010; Colón et al. 2010; Scaglia et al. 2011; Pognani et al. 2012a), for the prediction of the stability of final products such as stabilized material for landfill or compost (Adani et al. 2006; Barrena et al. 2014) and as a tool to include the performance of biological waste treatments when assessing environmental impacts of different waste treatment technologies (Colón et al. 2012).

Therefore, the main goal of this work was to compare the efficiency in terms of biowaste stabilization, using respirometric indices, of the main biological treatments used in MBT facilities currently operated in Europe. Six MBT facilities (8 MSW treatment lines) treating a total amount of 856,000 tons/year were analysed in depth. More than 100 respirometric indices including both dynamic and cumulative respiration indices were determined at different stages of these plants to analyse the real performance of these facilities. To our knowledge, no work of this magnitude has been previously published.

2. Materials and methods

2.1. MBT facilities

Table 1 shows the studied MBT facilities and their main treatment characteristics. The facilities were located in Spain and France. Although there are no two identical facilities, Figure 1 shows a typical layout of a MBT plant covering its main treatment stages (mechanical-biological pre-treatment, biological treatment and post-treatment). The studied MBT facilities were classified according to two different categories. On one side, MBT facilities were classified according to the input waste: mixed MSW or source-selected OFMSW. On the other, since the main difference among plants was the biological treatment during the decomposition stage, MBT plants under study were classified according to two groups: i) plants that combine anaerobic and aerobic biological treatments or ii) purely aerobic treatment plants.

Since pre-treatments and post-treatments were relatively similar in all MBT facilities under study (Table 1 and Figure 1) and the main difference among plants was the biological treatment, only a detailed explanation of biological treatments is given:

- MBT-1: This MBT plant is located in Spain. Mixed MSW and OFMSW are treated in this plant. MSW and OFMSW are treated separately in two independent lines.
    a. MBT-1.1: The MSW line has a waste treatment capacity of 155,000 tons/year. The biological treatment includes three different processes. The first one is a pre-treatment that takes place in a rotating drum biostabilizer with a retention time of 2 days, which main goal is to pre-hydrolyze the organic matter. Then, the pre-hydrolyzed material is composted during 2 weeks in composting tunnels. Finally, the maturation stage also takes place in composting tunnels for an additional week.
    b. MBT-1.2: The source-selected OFMSW line has a waste treatment capacity of 75,000 tons/year. After pre-treatment, the organic fraction is anaerobically digested in two digesters with a total volume of 6,700 m^3. The plant uses the BTA® process, in which the material is processed at a total solids concentration of 6 % (wet anaerobic digestion) and under mesophilic conditions (37 ºC) during 20 days. Then, the digested sludge is centrifuged and the solid fraction is mixed with bulking agent (pruning

    wastes in a 2:1 ratio) and composted during one week using composting tunnels.

- MBT-2: This MBT plant is located in Spain. Mixed MSW and OFMSW are treated separately in two independent lines in this plant.
    a. MBT-2.1: The MSW line has a waste treatment capacity of 160,000 tons/year. After the pre-treatment, the organic fraction is composted during 2 weeks in composting tunnels. Then, the maturation stage takes place in trenches (with aeration and moistening) during 2 additional weeks.
    b. MBT-2.2: The source-selected OFMSW line has a treatment capacity of 100,000 tons/year. The mechanically pre-treated organic matter is anaerobically digested in two digesters with a total volume of 4,500 m^3. The plant uses the Valorga® process, in which the material is processed in solid-state (20 % of total solids) and under mesophilic conditions (38 ºC) during 21 days. The digested solid fraction (press-screw digested cake) is mixed with bulking agent (pruning wastes in a 2:1 ratio) and composted in composting tunnels during one week to stabilize and sanitize the material. On the contrary, the centrifuge digested cake is thermally sanitized without further biological treatment.
- MBT-3: This MBT plant is located in Spain. Only mixed MSW is treated in this facility. The waste treatment capacity is 45,000 tons/year. After pre-treatment, the organic fraction is composted in a trench-based reactor (Biomax-G®) during 21 days in which both decomposition and maturation stages take place inside the same reactor. Aeration and moisture are controlled during the process.

- MBT-4: This MBT plant is located in Spain. Only mixed MSW is treated in this facility. The waste treatment capacity is 250,000 tons/year. The organic fraction from mechanical pre-treatment is anaerobically digested in four digesters with a total volume of 3,600 m^3. The Valorga® process is used, in which the material is processed in solid-state (35 % of total solids) and under mesophilic conditions (38 ºC) during 21 days. The digested solid fraction is then mixed with bulking agent (pruning wastes in a 1:1 ratio) and composted in composting tunnels for one week. Finally, the material is cured during four weeks in turned windrows.
- MBT-5: This MBT plant is located in France. Only source-selected OFMSW is treated in this facility. The OFMSW treatment capacity is 27,000 tons/year. The organic fraction is anaerobically digested in a digester with a volume of 3,100 m^3. The Valorga® process is used, in which the material is processed in solid-state (20 % of total solids) and under thermophilic conditions (55 ºC) during 21 days. The digested solid fraction (including press digested cake and centrifuge digested cake) is then composted during only two days in composting tunnels (no bulking agent is added because the organic matter itself has a high content of pruning wastes). Finally, the curing stage is finished in turned windrows with a retention time of two weeks.
- MBT-6: This MBT plant is located in France. Only mixed MSW is treated in this facility. The MSW treatment capacity is 44,000 tons/year. The biological treatment includes three different processes. The first one is a pre-treatment that takes place in a rotating drum biostabilizer with a retention time of 3 days. Then, the pre-hydrolyzed material is anaerobically digested in two digesters with a total volume of 3,000 m^3. The plant uses the Valorga® process, in which the material is processed in solid-state (22 % of total solids) and under mesophilic

conditions (37 ºC) during 21 days. The digested solid fraction is mixed with bulking agent (pruning wastes in a 1:1 ratio) and composted in composting tunnels during one week to stabilize and sanitize the material.

2.2. Sampling

A total amount of 55 samples were collected from April 2013 to September 2014. Sampling points were selected taking into account the most significant stages of MBT plants (Figure 1). Other sampling points not included in Figure 1 were also sampled for subsequent analysis; i.e, in plants relying on anaerobic digestion the different solid fractions obtained from the dehydration of digested materials were analysed (the mixture of these fractions is considered the output of the decomposition stage). The entire sampling process took place in one day per MBT facility.

Different sampling procedures were used depending on the sampling point. When samples were taken from composting/raw material piles, the bulk-integrated sample was obtained from eight different locations of each pile giving a final mass of approximately 30 kg. In continuous flow units (conveyors, pumps, dehydration systems, etc.), a subsample of around 5-6 kg was taken every 5 minutes, to finally obtain a sample of 30 kg. Then, the integrated sample was manually mixed in the laboratory and reduced to several sub-samples of approximately 1-1.5 kg using the quartering method, which were later used to carry out all the analytical procedures.

Only the biodegradable fraction was analysed (organic matter and paper), which means that all improper materials (plastic, glass, metal, etc.) were removed prior to physical-chemical characterization and respirometric tests. Samples were immediately frozen and stored at -20 ºC after collection. Before analysis, samples were thawed at room temperature for 24 h (Pognani et al. 2012b).

2.3. Respirometric tests

The Dynamic Respiration Index (DRI) was used as a measure of the biological activity of the material. This measure is related to the biodegradable organic matter in the sample and it is widely used in scientific literature. In this study, microbial respiration was measured as the oxygen consumption in a dynamic respirometer (Ponsá et al. 2010b), which is based on the methodology described by Adani et al. (Adani et al. 2006). Respiration was analysed in terms of long- and short-term indices:

(i) DRI_{24} (mg O_2 g^{-1} DM h^{-1}) was determined as the average of 24 instantaneous respiration indices (DRIi) obtained during the most intense 24h of biological activity (highest values of DRIi).

(ii) AT_4 (mg O_2 g^{-1} DM) was determined as the cumulative oxygen consumption recorded during 96h (4 days) through numerical integration of DRIi obtained during 96h.

The setup used in this work is described in Ponsá et al. (2010a). Briefly, 150 g of organic sample were placed in a 500 mL Erlenmeyer flask that was introduced in a water bath at 37 ºC. A constant airflow was supplied to the sample and the on-line oxygen content in the exhaust gas was monitored. From oxygen concentration vs. time curves, a dynamic respirometric index (DRI) related to oxygen consumption was obtained from the sample. All measurements were carried out in triplicates. Low porosity samples (anaerobically digested materials) were mixed with an inert bulking agent. This bulking agent consisted of small pieces (20 x 10 mm) of dishcloths (Spontex, Iberica) in a 1:10 wet weight ratio (Spontex:Sample) that were chosen to improve the sample porosity without affecting the respiration value (Puyuelo et al. 2011).

2.4. Analytical methods

Water content, dry matter (DM) and organic matter (OM) contents were determined according to standard procedures (The US Department of Agriculture and The US Composting Council, 2001). Three replicates were analysed for each sample.

2.5. Statistical analysis

Shapiro-Wilks tests were conducted to assess the normality of data (p=0.05) and Levene's test were conducted to assess the homogeneity of variances (p=0.05). Once normality and homogeneity of variances were ensured, parametric tests (one-way and two-way ANOVA) were performed to statistically compare the performance of MSW and OFMSW treatment lines previously explained. Statistical tests were conducted using SPSS 18 (SPSS Inc., Chicago, USA).

3. Results and discussion

3.1. Respirometric balances as a tool to analyse MBT facilities

The typical approach to study the efficiency and performance of MBT plants is to carry out mass balances, as previously reported (Pognani et al., 2012a; Colazo et al., 2015). However, in this work, a novel approach to assess the performance of MBT plants based on RI balances (DRI_{24} and AT_4) is developed as decision support tool. In scientific literature, respiration indices have been mainly used to assess the final quality of composts (Barrena et al., 2014; Adani et al., 2006) and, to a lesser extent, to analyse the performance of composting processes (Pognani et al., 2011; Ponsá et al., 2010b). As an example of the use of respiration indices as decision support tool, Figure 2 shows a flowchart representing the DRI_{24} and AT_4 balances of MBT-2.2. In this figure, RIs are shown together with the RI reduction (%) at each processing stage as well as the cumulative RI reduction (%) throughout the entire process. Figures showing the performance of all MBT facilities analysed can be found in the supplementary information (Figure 1S to Figure 8S).

Flowcharts permit to easily identify the key stages of the process along with possible bottlenecks. As an example, Figure 2 shows that a high efficiency is achieved in the overall process since a total RI reduction higher than 95 % is obtained. However, most of this reduction (85%) is due to the pre-treatment plus the anaerobic digestion stages. Only a small fraction (10%) is due to the final composting stage. Although a high efficiency is achieved, these efficiencies do not consider the refuse produced in the plant during the pre-treatment, which corresponds to around 17 % of the total input mass in this particular case. It is necessary to take into account that the refuse from the pre-treatment still has biological activity ($DRI_{24} = 1.07$ mg O_2 g DM^{-1} h^{-1} and $AT_4 = 75$ mg O_2 g DM^{-1}) and thus cannot be considered stabilized, which means that a large amount of organic matter suitable to produce biogas and compost is lost. Moreover, such organic matter will end up in a landfill contributing to environmental impact categories such as global warming and eutrophication, among others (Colón et al., 2012). In any case, a complete picture of the MBT performance is obtained when the characteristics of the rejected materials are included (Pognani et al., 2012a).

Figure 2 also shows that the most easily biodegradable matter coming from the AD output (centrifuge digested cake, DRI_{24}= 1.08 mg O_2 g DM^{-1} h^{-1}, DRI_{24}= 2.20 mg O_2 g VS^{-1} h^{-1}), which cannot be considered a stabilized material, does not follow a maturation treatment but is only thermally sanitized. Then, a biological treatment such as composting should be carried out to improve the final stability of this fraction. On the contrary, the most stable fraction (screw-press digested cake, DRI_{24}= 0.66 mg O_2 g DM^{-}

^{1} h^{-1}, DRI_{24}= 1.53 mg O_2 g VS^{-1} h^{-1}) is composted in a maturation/sanitation final stage. Finally, it can be observed that, in general, RI increases when bulking agent is added to the screw-press digested cake (DRI_{24} increases 27% and AT_4 increases 8%), which means that the bulking agent (pruning waste) contains a significant amount of biodegradable organic matter (leaves, grass, etc.). This fact has been previously observed and it must be considered when using this material as bulking agent in MBT composting stages (Ponsá et al., 2008).

It is worth mentioning that this novel approach based on RI to analyse a MBT plant can be very useful for plant managers and designers to easily identify the critical points of the process and, consequently, it is envisaged as a powerful decision support tool.

3.2. MBT relying on composting technologies

Results of the evolution of RI for MSW treated at MBT facilities relying solely on composting technologies are shown in Figure 3 (RIs together with the total solid content and the volatile solid content can be found in Table S1 of the supplementary information). RIs are expressed on a dry matter basis because the organic matter content varied significantly as biodegradation process occurred. Organic matter basis has been exclusively used to normalise the final material stability for comparison with some national stability limits (section 3.3).

As reported in Ponsá et al. (2010b) a decrease of both DRI_{24} and AT_4 is observed during the pre-treatment stage. This confirms that operations involved in the pre-treatment (pit storage and the mechanical pre-treatment) provoke the biodegradation of the most rapidly biodegradable fraction contained in this material (Ponsá et al., 2011). The average reduction during the pre-treatment stage at MBT-2.1 and MBT-3 was 34 % and 30 % for DRI_{24} and AT_4, respectively. It is of special interest the reduction attained at

MBT-1.1 where the pre-treatment stage also includes a pre-hydrolysis treatment by means of a rotating drum biostabilizer (RDB). In this case, the RI reduction was as high as 61 % and 53 % for DRI_{24} and AT_4, respectively, which corresponded to the stage of the entire process where the reduction of RI was larger. Although results are very promising, further research is needed to completely understand the behaviour of the biodegradable fraction (organic matter and paper/cardboard) during MSW pre-treatment by means of RDB operated at short retention times. Only the performance of RDB operated with longer retention times related to a complete composting process (from 7 to 20 days) has been reported in literature (Kalamdhad et al. 2009; Kalamdhad et al. 2008). RDB operated at short retention times (1 to 3 days) has also been previously reported as a pre-treatment step of MSW but its performance in terms of stability/organic matter degradation has not yet been studied (Zhu et al. 2009). To our knowledge, these results are the first study in which RDB operating at short retention times has been analysed using respiration indices as performance indicators.

As expected, the decomposition stage (tunnel in MBT 2.1 and trenches in MBT-3) has a major effect on the stabilization of MSW in MBT facilities without RDB. The RI reduction ranged from 40 to 65% for both DRI_{24} and AT_4, respectively.

Average DRI_{24} and AT_4 for biostabilized materials were 1.3 ± 0.2 mg O_2 g DM^{-1} h^{-1} and 104 ± 19 mg O_2 g DM^{-1}, respectively, which implies a DRI_{24} reduction from input to biostabilized materials ranging from 66 to 79 % (71 % on average) and an AT_4 reduction ranging from 58 to 78 % (66 % on average).

Figure 3 shows that a low RI reduction was obtained from the decomposition output stream to the final biostabilized materials (except in MBT-2.1) indicating a poor performance of the maturation stage. To confirm this hypothesis, a one-way ANOVA test was used to compare the RI from decomposition output, maturation output and biostabilized material. Neither the DRI_{24} (p=0.42) nor the AT_4 (p=0.76) showed significant differences. Hence, it can be concluded that, as a general rule, the maturation stage does not contribute significantly to the stabilisation of the material in MBT facilities and it is a possible bottleneck to improve MBT overall performance. This fact can be explained by the short duration of the maturation stage (usually only one week). Moreover, operating conditions such as the moisture content, free air space or oxygen content are of outmost importance to promote biodegradation during the maturation stage. However, this stage is usually carried out under low-controlled conditions, which also contributes to the overall poor performance of the process.

3.3. MBT relying on anaerobic digestion

Results of the evolution of RI for MSW and OFMSW treated at MBT facilities relying on anaerobic digestion are shown in Figure 4 (RIs together with the total solid content and the volatile solid content can be found in Table S2 of the supplementary information).

Since pre-treatment designs are fairly similar in all MBT facilities, the RI reduction pattern observed during the pre-treatment stage is also confirmed. The average reduction during this stage was 19 % and 24 % for DRI_{24} and AT_4, respectively. However, this pattern was not observed in MBT-5. In this particular case, the RI increased from input material to pre-treated material. In this case, it must be noted that the input material in MBT-5 contained a great amount of shredded pruning wastes that were partially removed during the pre-treatment process, which concentrates the amount of easily biodegradable organic matter, thus explaining the RI increase. The considerable stabilization during the pre-treatment process observed in most cases has important implications in the design of MBT plants, especially those relying on AD processes as main stage. For instance, the loss of organic matter during the pre-treatment is expected to provoke a decrease in the biogas yield when compared to that of untreated input material determined in batch BMP tests, which are the values typically considered when designing anaerobic reactors (Ponsá et al. 2010b). In this sense, the impact of a RDB pre-treatment, which achieved a DRI_{24} and AT_4 reduction of 57% and 61%, respectively, in the biogas production should be further studied in MBT-6. Zhu et al. (2009) reported biogas yields ranging from 457 to 557 ml g VS^{-1} and a methane content ranging from 57 to 60 % when different materials (MSW, MSW and paper mixture, biosolids and biosolids and paper mixture) previously pre-treated by means of a RDB were anaerobically digested. These figures are in the upper range (or even higher) than the typically reported biogas yields ranging from 350 to 450 mL g VS^{-1} (Ponsá et al. 2008; Pognani et al. 2010), which means that RDB could be a promising pre-treatment for anaerobic digestion. However, further research is needed to confirm this pattern.

The AD process was mainly responsible for stabilising the organic matter. Average DRI_{24} and AT_4 for decomposition output (mixture of solid fractions of AD output) were 0.75 ± 0.29 mg O_2 g DM^{-1} h^{-1} and 50 ± 19 mg O_2 g DM^{-1}, respectively, implying RI reductions (in both DRI_{24} and AT_4) ranging from 75 to 90%. The stability of the materials from the AD process, even without a maturation stage, was significantly higher ($p<0.01$) in average than the stability results obtained in final materials of MBT plants relying solely on composting processes.

On the contrary, the maturation stage in the composting MBT plants by means of tunnel composting of the digested solid fractions had an important effect on the final RI. Average reductions of 70 and 65 % of the DRI_{24} and AT_4, respectively, were achieved during this stage contributing to overall RI reductions (from input materials to final compost/biostabilized material) ranging from 87 to 96 % in both DRI_{24} and AT_4. The maturation stage also contributes to obtain a sanitized material; which is necessary in plants where AD reactors are working at mesophilic temperatures.

3.4. Compost quality: Comparison of technologies

Since some national regulations on stability use organic matter (often expressed as volatile solids) as the basis for stability measurements, Table 2 shows the RI of biostabilized materials based on a volatile solids basis. The European Commission (2001) recommends a stability limit of 1.0 mg O_2 g VS^{-1} h^{-1}. MBT facilities relying solely on composting technologies did not reach the proposed stability limit (Table 2). On the contrary, all MBT plants relying on AD technology during the decomposition stage achieved the proposed stability limit, with the exception of MBT-4.

As explained in Section 2.1, the MBT facilities studied were classified according to two different parameters: (i) the type of input waste (mixed MSW or source-selected OFMSW) and (ii) the main biological decomposition technology (anaerobic digestion or composting). Therefore, RI reductions were subjected to a two-way analysis of variance at two levels of “input waste” (MSW, source-selected OFMSW) and two levels of “treatment technology” (AD and composting). In order to increase the number of samples, data reported in previously published works (Barrena et al. 2014; Ponsá et al. 2010a; Pognani et al. 2011) using the same equipment and methodology were added to the analysis. Since composting of source-selected OFMSW is highly variable in time (ranging from one to six months) and in technology (home composting, static and aerated piles, trenches, tunnels, etc.), only MBT facilities using composting tunnels as a decomposition stage and an overall composting process taking place in less than 2 months (as in the MBT plants analysed in this work) were included in the analysis.

A two-way ANOVA was conducted to examine the effect of the treatment technology and the input waste on the final values of DRI_{24} and AT_4. There was no statistically significant interaction between the effects of treatment technology and the input waste neither in the DRI_{24} ($F(1,10)=3.142$, $p=0.107$) nor in the AT_4 ($F(1,10)=3.455$, $p=0.093$). However, a simple main effects analysis showed that lower DRI_{24} ($F(1,10)=45.164$, $p<0.001$) and AT_4 ($F(1,10)=50.845$, $p<0.001$) were achieved when AD was used as the main treatment technology instead of composting tunnels during the decomposition stage. This means that a high grade of stabilization is achieved during the overall treatment process. Figure 5 shows a boxplot for both DRI_{24} and AT_4 when treating both OFMSW and MSW using AD and composting technologies. It can be observed that the difference in median values and even the extreme values (maximum value for AD with minimum value for composting) are not overlapped in any case. Finally, the main effect of "input waste" was non-significant for both DRI_{24} and AT_4 ($p>0.05$). Hence, although the input waste had different composition (MSW or source-selected OFMSW), the same grade of stabilization was obtained when the same treatment technology was applied. This fact is of outstanding relevance for the design of future MBT plants, as it highlights the importance of selecting an appropriate technology regardless the type of organic waste treated.

This work demonstrates that a high grade of stability can be obtained in both MSW and source-selected OFMSW treatments. However, other important properties affect the final quality and limit the utilization of compost/biostabilized materials. Although not specifically addressed in this work, the metal content is one of the main limiting parameters. Many sources of heavy metals are found in compost, particularly products derived from household municipal solid waste. Metals are present in plastics, paints and inks, bodycare products and medicines and household pesticides (Bardos 2004; Smith

2009). Consequently, composts derived from source-selected waste streams are generally reported to contain smaller amounts of heavy metals compared to mechanically-sorted products (Epstein et al. 1992; Amlinger et al. 2004). However, some authors (Pognani et al. 2012a) reported metal contents slightly higher than those recommended for Class A compost according to the Spanish legislation (Ministerio de la Presidencia, 2005). Biostabilized materials produced from MSW generally contain larger metal contents than those from source separated OFMSW. However, a review of international metal content data (Smith 2009) showed that mechanical treatment can produce a final product compliant with current European legislation limits (WRAT/EA, 2007; Ministerio de la Presidencia, 2005) indicating that modern mechanical pre-treatment processes can effectively remove the main sources of contaminants. Huerta-Pujol et al. (2011) reported significant differences when comparing the metal and nutrient content of source-separated OFMSW and MSW final materials (compost or biostabilized material). In general, source separated OFMSW samples presented higher nutrient contents (P, K, Na, Ca) and lower heavy metal concentration (Cr, Pb) than MSW samples. On the contrary, no statically significant differences were found for Mn, Zn, Cu. Although published studies in general suggest a higher metal content in mixed MSW than in source-selected OFMSW, a high grade of variability exists and it can not be established as a rule. Therefore, the uses of these materials should not be solely based on its origin but on its specific quality.

3.5. Correlation between cumulative and non-cumulative respiration indices

RI indices used in this work provide complementary information; AT_4 quantifies the biodegradable organic matter content of a given sample whereas DRI_{24} is a measure of the biodegradability rate, being high or moderate (Barrena et al. 2014). Ponsá et al.

(2010a) reported a positive correlation between dynamic and cumulative respiration indices for raw MSW samples although stated that more evidence to generalize this positive correlation would be necessary for other organic wastes such as source-selected OFMSW or MSW at different stages of the stabilisation process in MBT plants. They also reported positive correlations between aerobic (DRI_{24}) and anaerobic tests (GB_{21}).
In this study, the correlation between DRI_{24} and AT_4 of all samples analysed (from fresh to highly stabilised samples) resulted in $AT_4 = 73.0\ DRI_{24}$ (DRI_{24} in mg O_2 g^{-1} DM h^{-1} and AT_4 in mg O_2 g^{-1} DM) while RIs can be found in Tables S1 and S2. A satisfactory correlation was found with a correlation coefficient (R^2) of 0.987. Thus, DRI_{24} and AT_4 can be positively correlated and both can be used as a reliable measure of the stability of the process and the stage of biodegradation of organic matter in an MBT plant.

To correlate general RI with more advanced parameters further studies should focus on the changes in the oxidation of organic matter during the treatment process. In this sense, electron transfer balances could be used as a novel approach for MBT plants as it is usually done in AD wastewater reactors with COD balances.

3.6. Cost considerations

It is extremely difficult to provide a detailed cost comparison for MBT plants because costs are not only dependant on the technology used (AD or composting). Other important factors are critical to determine final operational costs such as treatment capacity, amount of impurities (therefore, requiring more mechanical pre-treatment) and, even more important, if there is source selection or not.

Cost analysis should focus on comparable parameters. In the plants studied herein, costs have many uncertainties to be used for comparison purposes among different plants. In most cases, treatment costs are the result of an agreement between a public administration and private companies managing MBT plants, therefore, costs include many more variables than strictly technological aspects. Taking into account all these limitations, the operation cost in Spain in 2016 was around 15 €/ton for MBT plants based on composting only and 45 €/ton for MBT plants based on AD + composting (Urbaser S.A., personal communication). These operational costs does not include any revenue neither from energy valorisation in AD (heat and/or electricity) nor compost selling in both AD and composting processes.

4. Conclusions

MBTs relying on anaerobic digestion as the main biological treatment produced final compost/biostabilized materials with a high grade of stability (0.24 ± 0.09 mgO_2 g^{-1} DM h^{-1} and 20 ± 9 mg O_2 g^{-1} DM). On the contrary, MBTs relying on composting showed a poor performance (1.3 ± 0.2 mg O_2 g^{-1} DM h^{-1} and 104 ± 18 mg O_2 g^{-1} DM). Although no statistical differences were found regarding the input material (MSW vs OFMSW), statistical significant differences were found regarding the stabilization of final products when treatment technologies (AD vs composing) were compared.

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Figures

Figure 1. Scheme of a typical mechanical-biological treatment plant. ☑ indicate sampling points.

Figure 2. DRI_{24} (mg O_2 g^{-1} DM h^{-1}) and AT_4 (mg O_2 g^{-1} DM) balances of MBT-2.2. "R" corresponds to the RI reduction (%) between two consecutive stages; "R_{ac}" corresponds to the cumulated RI reduction (%). Negative R (%) are consequence of adding biodegradable pruning waste (prior to maturation stage) to the digested press-screw cake, which increases the RI values.

Figure 3. Evolution of Respiration Index in the mechanical-biological treatment plant relying on Composting. Average of all plants is presented with standard deviation. a) Dynamic Respiration Index (DRI_{24}) and b) Cumulative Respiration Index (AT_4).

Figure 4. Evolution of Respiration Index in the mechanical-biological treatment plant relying on Anaerobic Digestion. Average of all plants is presented with standard deviation. a) Dynamic Respiration Index (DRI_{24}) and b) Cumulative Respiration Index (AT_4).

Figure 5. DRI_{24} (a) and AT_4 (b) boxplots for MBTs relying on Anaerobic Digestion and Composting.

Figure 1.

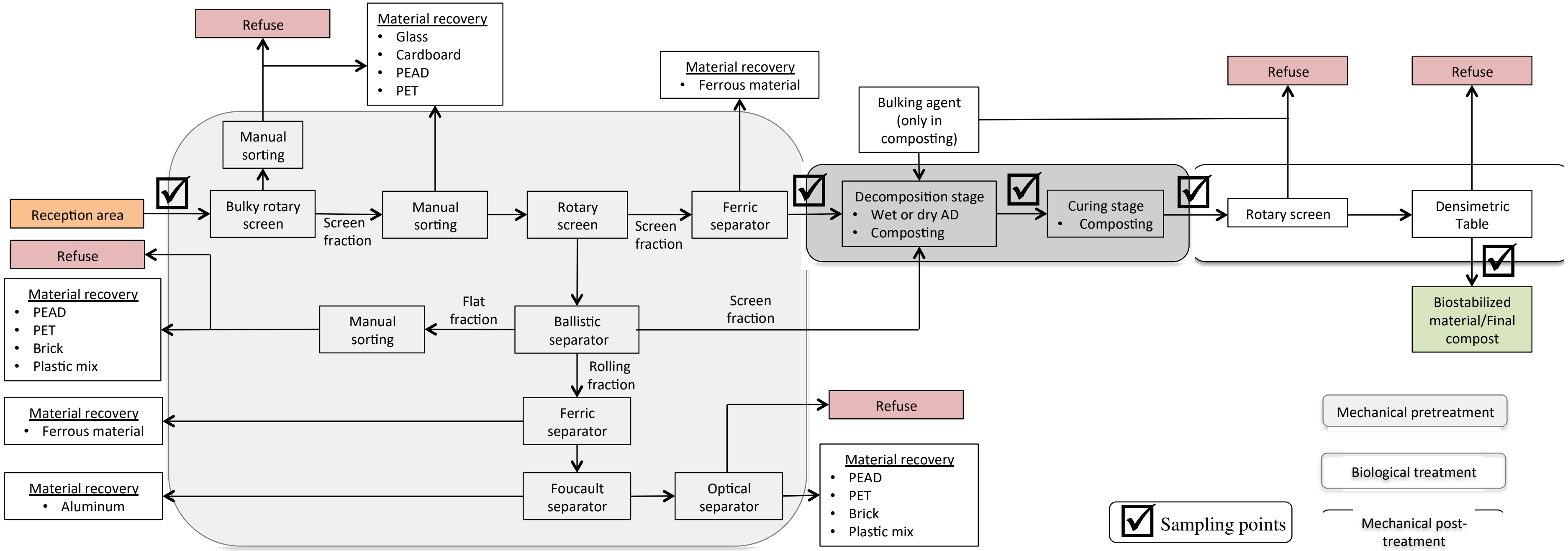
Reception area
Refuse
Bulky rotary screen
Manual sorting
Refuse
Material recovery
Glass
Cardboard
PEAD
PET
Screen fraction
Manual sorting
Rotary screen
Screen fraction
Ferric separator
Material recovery
Ferrous material
Bulking agent (only in composting)
Decomposition stage
Wet or dry AD
Composting
Curing stage
Composting
Rotary screen
Refuse
Densimetric Table
Refuse
Biostabilized material/Final compost
Material recovery
PEAD
PET
Brick
Plastic mix
Manual sorting
Flat fraction
Ballistic separator
Screen fraction
Rolling fraction
Ferric separator
Material recovery
Ferrous material
Foucault separator
Optical separator
Refuse
Material recovery
Aluminum
Material recovery
PEAD
PET
Brick
Plastic mix
Sampling points
Mechanical pretreatment
Biological treatment
Mechanical post-treatment

Figure 2.

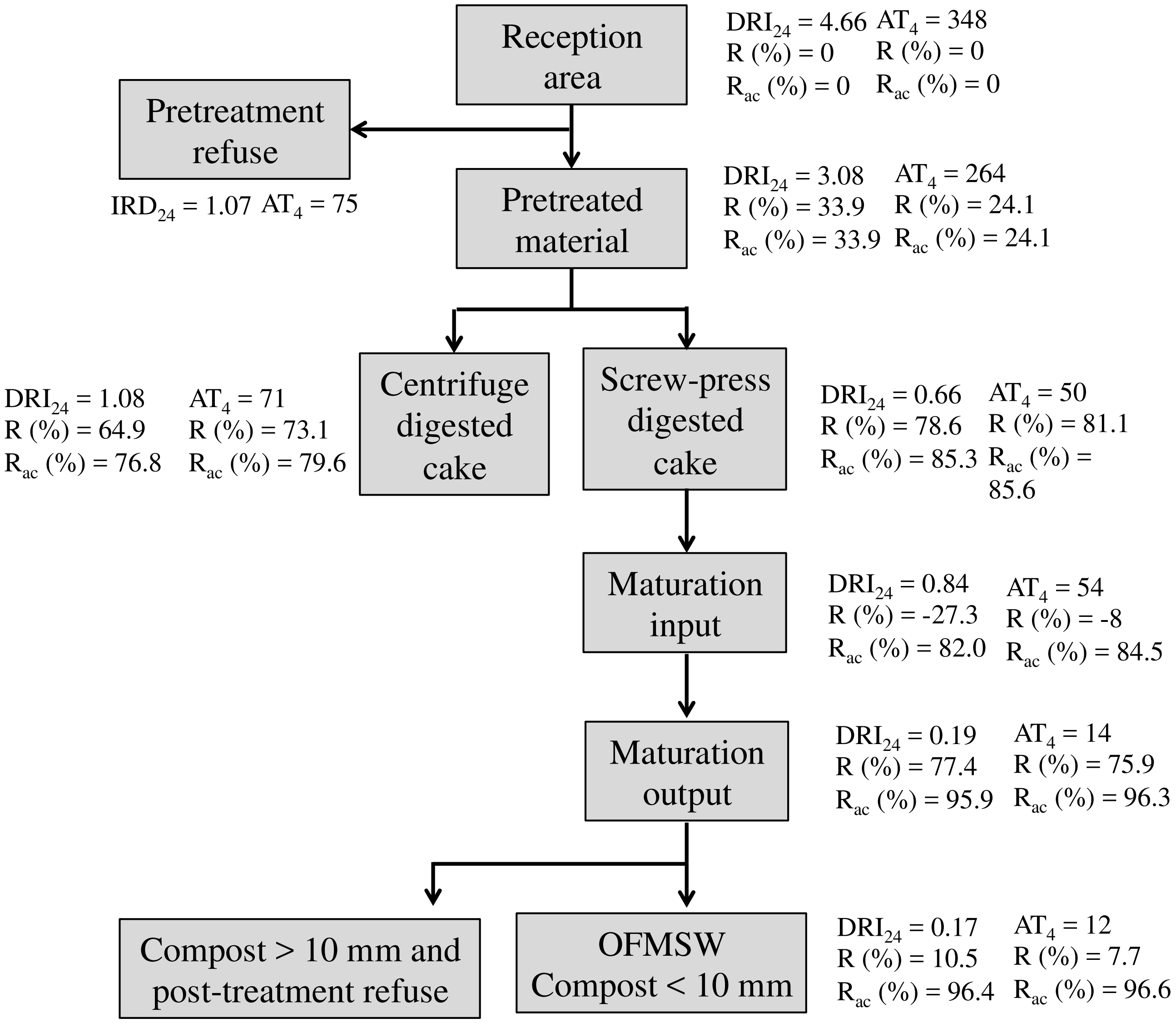
Reception area
$\mathrm{DRI}_{24} = 4.66$
$\mathrm{R}\ (\%) = 0$
$\mathrm{R}_{ac}\ (\%) = 0$
$\mathrm{AT}_4 = 348$
$\mathrm{R}\ (\%) = 0$
$\mathrm{R}_{ac}\ (\%) = 0$
Pretreatment refuse
$\mathrm{IRD}_{24} = 1.07$
$\mathrm{AT}_4 = 75$
Pretreated material
$\mathrm{DRI}_{24} = 3.08$
$\mathrm{R}\ (\%) = 33.9$
$\mathrm{R}_{ac}\ (\%) = 33.9$
$\mathrm{AT}_4 = 264$
$\mathrm{R}\ (\%) = 24.1$
$\mathrm{R}_{ac}\ (\%) = 24.1$
$\mathrm{DRI}_{24} = 1.08$
$\mathrm{R}\ (\%) = 64.9$
$\mathrm{R}_{ac}\ (\%) = 76.8$
$\mathrm{AT}_4 = 71$
$\mathrm{R}\ (\%) = 73.1$
$\mathrm{R}_{ac}\ (\%) = 79.6$
Centrifuge digested cake
Screw-press digested cake
$\mathrm{DRI}_{24} = 0.66$
$\mathrm{R}\ (\%) = 78.6$
$\mathrm{R}_{ac}\ (\%) = 85.3$
$\mathrm{AT}_4 = 50$
$\mathrm{R}\ (\%) = 81.1$
$\mathrm{R}_{ac}\ (\%) = 85.6$
Maturation input
$\mathrm{DRI}_{24} = 0.84$
$\mathrm{R}\ (\%) = -27.3$
$\mathrm{R}_{ac}\ (\%) = 82.0$
$\mathrm{AT}_4 = 54$
$\mathrm{R}\ (\%) = -8$
$\mathrm{R}_{ac}\ (\%) = 84.5$
Maturation output
$\mathrm{DRI}_{24} = 0.19$
$\mathrm{R}\ (\%) = 77.4$
$\mathrm{R}_{ac}\ (\%) = 95.9$
$\mathrm{AT}_4 = 14$
$\mathrm{R}\ (\%) = 75.9$
$\mathrm{R}_{ac}\ (\%) = 96.3$
Compost > 10 mm and post-treatment refuse
OFMSW Compost < 10 mm
$\mathrm{DRI}_{24} = 0.17$
$\mathrm{R}\ (\%) = 10.5$
$\mathrm{R}_{ac}\ (\%) = 96.4$
$\mathrm{AT}_4 = 12$
$\mathrm{R}\ (\%) = 7.7$
$\mathrm{R}_{ac}\ (\%) = 96.6$

Figure 3.

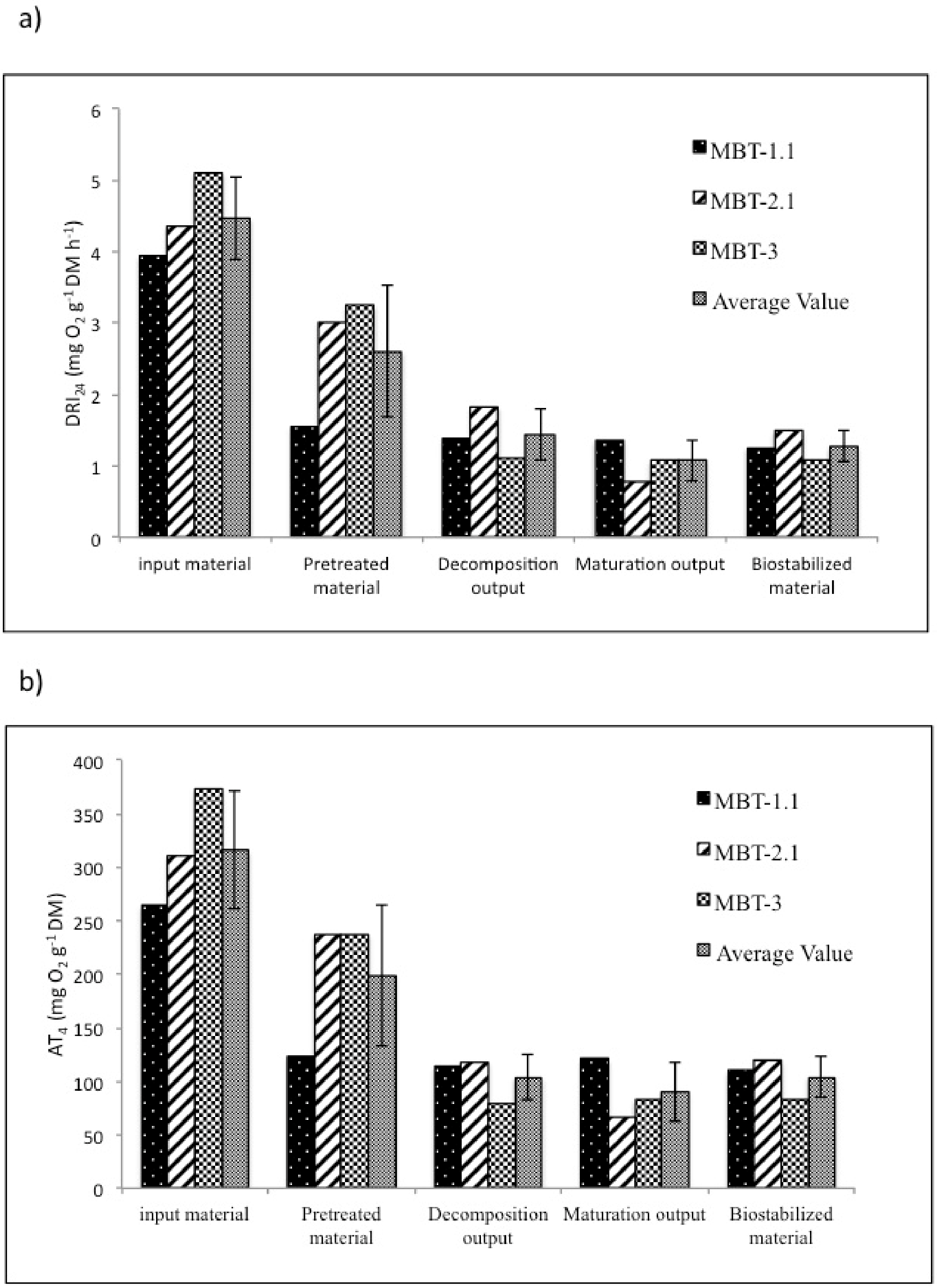
a)
6
5
4
3
2
1
0
DRI_{24} (mg O_2 g^{-1} DM h^{-1})
MBT-1.1
MBT-2.1
MBT-3
Average Value
input material
Pretreated material
Decomposition output
Maturation output
Biostabilized material
b)
400
350
300
250
200
150
100
50
0
AT_4 (mg O_2 g^{-1} DM)
MBT-1.1
MBT-2.1
MBT-3
Average Value
input material
Pretreated material
Decomposition output
Maturation output
Biostabilized material

Figure 4.

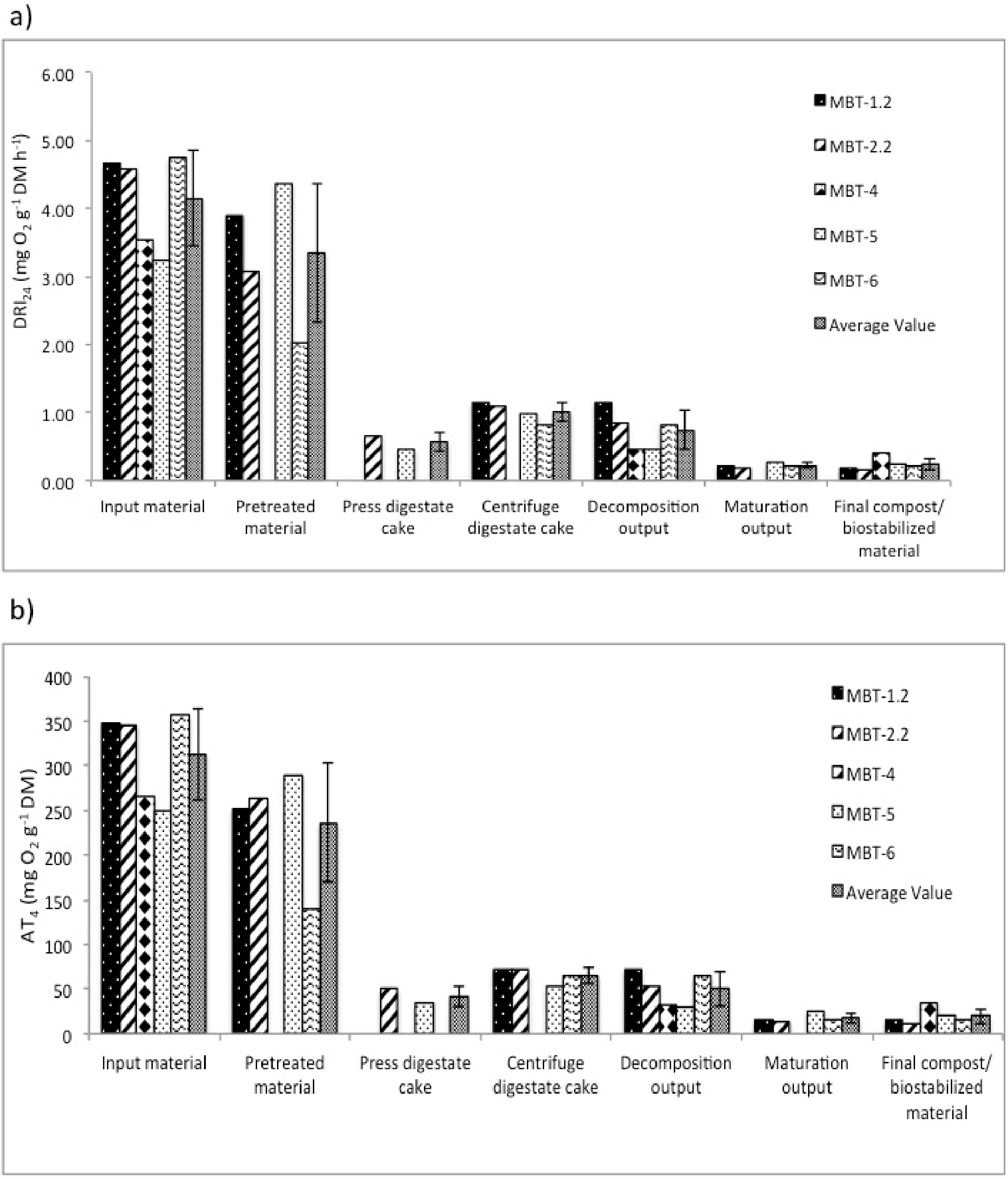
a)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
DRI$_{24}$ (mg O$_2$ g^{-1} DM h^{-1})
MBT-1.2
MBT-2.2
MBT-4
MBT-5
MBT-6
Average Value
Input material
Pretreated material
Press digestate cake
Centrifuge digestate cake
Decomposition output
Maturation output
Final compost/ biostabilized material
b)
400
350
300
250
200
150
100
50
0
AT$_4$ (mg O$_2$ g^{-1} DM)
MBT-1.2
MBT-2.2
MBT-4
MBT-5
MBT-6
Average Value
Input material
Pretreated material
Press digestate cake
Centrifuge digestate cake
Decomposition output
Maturation output
Final compost/ biostabilized material

Figure 5.

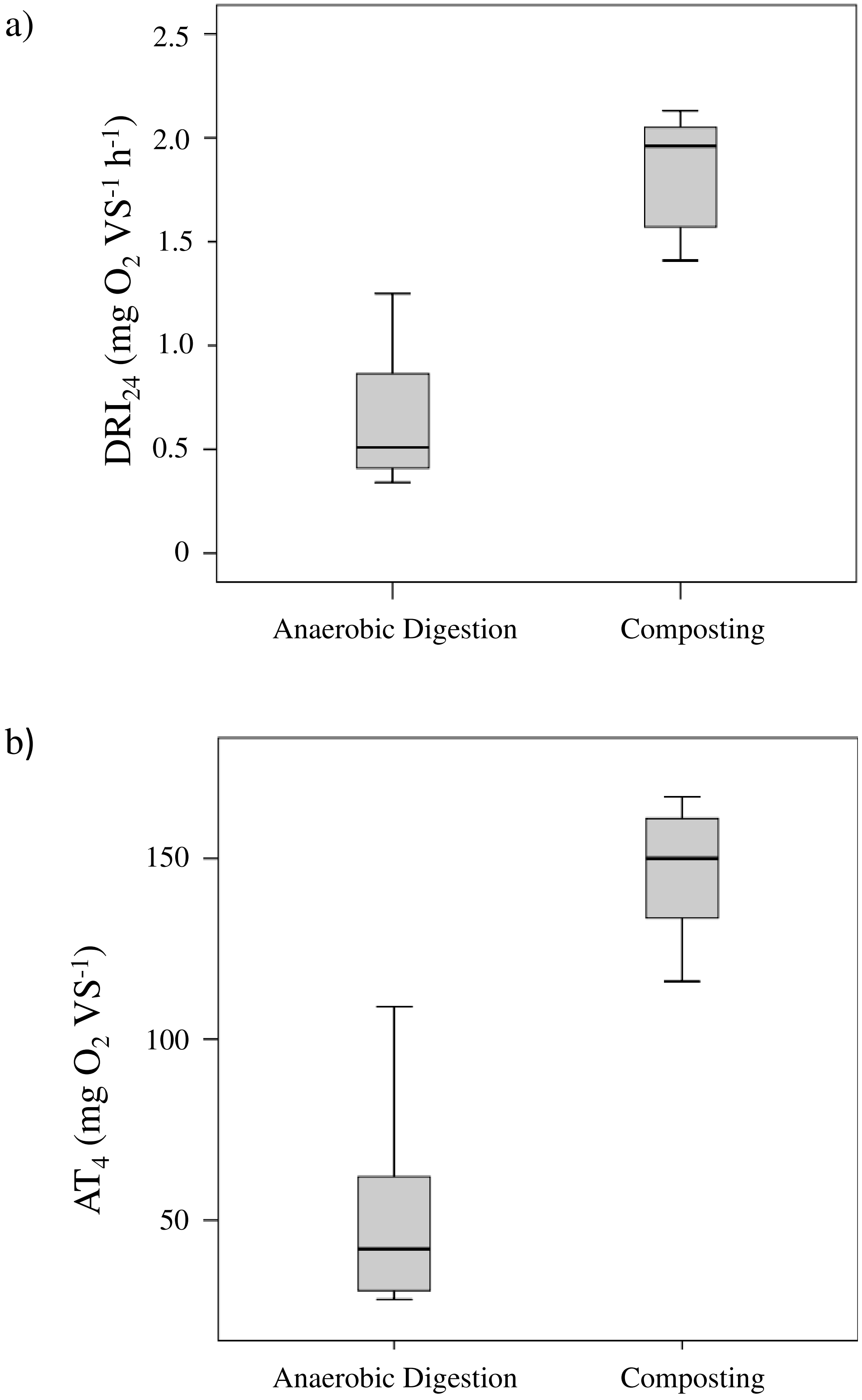
a)
DRI$_{24}$ (mg O$_2$ VS^{-1} h^{-1})
2.5
2.0
1.5
1.0
0.5
0
Anaerobic Digestion
Composting
b)
AT$_4$ (mg O$_2$ VS^{-1})
150
100
50
Anaerobic Digestion
Composting

Table 1. Main characteristics of the studied facilities.

ID	Input waste	dry pre-treatment	wet pre-treatment	decomposition stage	maturation stage	post-treatment
MBT-1.1	Mixed MSW	rdb + rs + ms + bs + fs + ecs	-	composting tunnel	composting tunnel	rs + dt
MBT-1.2	SS-OFMSW	rs + ms+ sh + bs + fs + ecs	pulper + hydrocyclone	wet AD	composting tunnel	rs + dt
MBT-2.1	Mixed MSW	rs + ms + sh + bs + fs + ecs	-	composting tunnel	trench-based reactor	rs + dt
MBT-2.2	SS-OFMSW	rs + ms+ sh + bs + fs	-	dry AD	composting tunnel	rs + dt
MBT-3	Mixed MSW	rs + bs + fs	-	trench-based reactor	-	-
MBT-4	Mixed MSW	rs + ms + fs +bs + vs	-	dry AD	composting tunnel + turned pile	rs + dt
MBT-5	SS-OFMSW	rs + ms+ sh + bs + fs + ecs	-	dry AD	composting tunnel + static pile	rs + dt
MBT-6	Mixed MSW	rdb + rs + vs + bs + fs + ecs	-	dry AD	composting tunnel	rs + dt

rdb: rotating drum biostabilizer; rs: rottary screen; vs: vibrating sieve; ms: manual sorting; sh: shredding; bs: ballistic separator; fs: ferric separator; ecs: eddy current separator (foucault); dt: densimetric table; vs: vibrating sieve separator.

Table 2. Respiration Indices (DRI_{24} and AT_4) of final compost/biostabilized materials expressed in volatile solid basis.

Final compost	ID	DRI_{24} (mg O_2 g^{-1} VS h^{-1})	AT_4 (mg O_2 g^{-1} VS)
Composting mixed-MSW	MBT-1.1	1.69	147
	MBT-2.1	1.45	116
	MBT3	1.96	150
	Average	1.70 ± 0.25	138 ± 19
Composting SS-OFMSW	Barrena et al. (2014)	2.13	157
	Barrena et al. (2014)	1.98	165
	Barrena et al. (2014)	2.12	167
	Barrena et al. (2014)	1.41	120
	Average	1.91 ± 0.34	152 ± 11
AD mixed-MSW	MBT-4	1.25	109
	MBT-6	0.41	32
	Ponsá et al. (2010)	0.98	71
	Average	0.88 ± 0.42	71 ± 38
AD SS-OFMSW	MBT-1-2	0.34	28
	MBT-2.2	0.41	29
	MBT-5	0.51	42
	Pognani et al. (2011)	0.75	53
	Average	0.50 ± 0.18	38 ± 12