A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant

Michele Pognani, Raquel Barrena, Xavier Font and Antoni Sánchez*

Composting Research Group
Department of Chemical Engineering
Escola d'Enginyeria
Universitat Autònoma de Barcelona
Bellaterra (Cerdanyola del Vallès, 08193-Barcelona, Spain)

* Corresponding author:
Antoni Sánchez
Tel.: (34) 93 5811019
Fax: (34) 93 5812013
E-mail: antoni.sanchez@uab.cat

Pre-print of: Pognani, M. et al. "A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant" in Waste management (Elsevier), vol. 32, issue 5 (May 2012) p. 799-805. The final versión is available at DOI 10.1016/j.wasman.2011.12.018

Abstract

In this study a combined anaerobic/aerobic full-scale treatment plant designed for the treatment of the source-separated organic fraction of municipal solid waste (OFMSW) was monitored over a period of one year. During this period, full information was collected about the waste input material, the biogas production, the main rejects and the compost characteristics. The plant includes mechanical pre-treatment, dry thermophilic anaerobic digestion, tunnel composting system and a curing phase to produce compost. To perform the monitoring of the entire plant and the individual steps, traditional chemical methods were used but they present important limitations in determining the critical points and the efficiency of the stabilization of the organic matter. Respiration indices (dynamic and cumulative) allowed for the quantitative calculation of the efficiency of each treatment unit. The mass balance was calculated and expressed in terms of Mg y^{-1} of wet (total) matter, carbon, nitrogen and phosphorous. Results show that during the pre-treatment step about 32% of the initial wet matter is rejected without any treatment. This also reduces the biodegradability of the organic matter that continues to the treatment process. About 50% of the initial nitrogen and 86.4% of the initial phosphorous is found in the final compost. The final compost also achieves a high level of stabilization with a Dynamic Respiration Index of 0.3 ± 0.1 g O_2 per kg of Total Solids per hour, which implies a reduction of 93% from that of the raw OFMSW, without considering the losses of biodegradable organic matter in the refuse (32% of the total input). The anaerobic digestion process is the main contributor to this stabilization.

Keywords: waste treatment plant; municipal waste; waste source-separation; mass balance; nitrogen; phosphorous; stability.

1. Introduction

The Organic Fraction of Municipal Solid Waste (OFMSW) is a highly biodegradable material; therefore the most suitable alternative ways of management are biological processes, such as composting and anaerobic digestion (Ağdağ and Sponza, 2005). Composting represents the main biological treatment technology used to treat the OFMSW, and in the last 10 years, the number of composting plants has been steadily increasing (Pognani et al., 2009).

Although industrial scale composting facilities have been constructed and operated in the recent years, the efficiency and the mass flow analysis of these facilities is still unclear. Several types of waste treatment plants have been used to perform partial mass balances to assess their performance and efficiency. Sommer and Dahl (1999) studied the nutrient and carbon balance during the composting process of deep litter. de Araújo Morais et al. (2008) identified the critical steps of a mechanical biological treatment plant located in France. This study highlighted the importance of a mass balance for assessing the actual performance of waste treatment plants. Also, Banks et al. (2011) performed a mass balance to study an anaerobic digestion plant of domestic food waste in terms of biogas and energy production. Other studies have been focused on specific biological treatment technologies performed at full-scale facilities (Correia et al., 2007; Correia et al., 2008; Vaz et al., 2008). However, there is a reduced number of works in which complex plants (including anaerobic digestion and composting) are studied in terms of mass balance using chemical and respiration measurements. The fate of the nutrients in the plants and the final stability reached are also poorly studied (Ponsá et al., 2008).

Mass balance in waste treatment plants is generally expressed as a function of wet matter or dry matter, but it is also interesting to express the mass balance as a function of other parameters, such as organic matter or oxidative organic matter (Araújo Morais et al., 2008). However, the analysis of the efficiency of organic waste treatment plants requires a reliable measure of the biodegradable organic matter content of the materials during the process steps. Respirometric indices (Adani et al., 2001; Barrena et al., 2005) and anaerobic assays such as the anaerobic biogas potential (ABP) (Ponsá et al., 2008; Pognani et al., 2010) can be useful to indicate the amount of readily biodegradable organic matter that has been decomposed during the overall process or a specific step.

Our approach in this paper is to assess the performance of a combined anaerobic/aerobic full-scale municipal source-separated waste treatment plant. To achieve this general objective, mass balance was performed through the entire plant and it was expressed as a function of wet matter, carbon, nitrogen and phosphorous content and compared to the evolution of the biodegradable organic matter content of the OFMSW followed by respiration indices. These indices were also used for the characterization of the efficiency of degradation of the biodegradable organic matter during the biological process. The final objective of this paper was to assess the efficiency of the different steps of the facility and to express the input/output steps in terms of Mg y^{-1} of carbon, nitrogen and phosphorous. This permits the evaluation of the plant performance from an overall point of view. To our knowledge, no similar works are reported in literature.

2. Materials and Methods

2.1. Plant characteristics

During one year a complete monitoring of a full-scale anaerobic digestion plus composting plant located in Barcelona (Spain) was performed. This facility is currently operating and has been designed to treat 25,000 Mg $year^{-1}$ of OFMSW coming from a street bin source-separated collection system. In this paper the facility is sub-divided into four main steps: pre-treatment step, anaerobic digestion, composting/curing phase and compost refining.

The facility configuration is presented in detail in Figure 1. The pre-treatment step was designed to concentrate organic matter before biological treatment and to remove inert materials. The anaerobic digestion process is based on the DRANCO (DRy ANaerobic Composting, OWS, Belgium) technology. It is a dry process at thermophilic temperature (50-55°C). The digester mixing is provided by the recirculation of the digested material (digestate). The retention time is 22 days and the digester capacity is 1700 m^3. The digestate composting process is performed in two phases: a first decomposition in aerated tunnels and a curing phase in turned piles.

Samples for the mass balance were collected from the most important points of the plant (Figure 1). The samples selected for the study were subdivided into input and output materials. As input materials the OFMSW, the diatomaceous earth and the bulking agent were identified. As output materials the pre-treatment refuse (waste from the ballistic separator of the pre-treatment step), the material rejected by the grinder/pump system, the leachate, the biogas, the compost refuse plus dust (from the compost refining process), and the final compost were identified. Pre-treatment output, anaerobic digestion output and composting phases outputs were also used as critical points to evaluate the yield of each step regarding the level of respiration stability achieved.

To assess the performance of the plant, the samples selected were also used to determine the biological and chemical characteristics of the waste at the different steps analyzed.

2.2. Respirometric and biogas potential assays

The procedure established in this study for the determination and calculation of the dynamic respiration index (DRI_{24h}) and the cumulative respiration activity (AT_4) is based on previous works (Adani et al., 2004; Barrena et al., 2005; Ponsá et al., 2008; Pognani et al., 2010). Briefly, it consists of several glass flask reactors, a thermostatic bath at 37ºC, a control cabinet, an oxygen sensor, an air supply system based on mass flow-meters and a personal computer unit. DRI was expressed as g of oxygen consumed per kg of total solids per hour (g O_2 kg^{-1} TS h^{-1}) and it is presented as an average of a duplicate measurement. It corresponds to the average value of maximum respiration activity during 24 hours. AT_4 was expressed as g of oxygen consumed per kg of total solids (g O_2 kg^{-1} TS), and it is also presented as an average of a duplicate measurement. Detailed information of both methods can be found elsewhere (Ponsá et al., 2010a)

ABP data was obtained according to Pognani et al. (2010) during 21 days of incubation of the samples under anaerobic conditions (ABP_{21}). DRI_{24h}, AT_4 and ABP_{21} were used to monitor the biodegradation of the organic matter and the efficiency of the treatment plant.

2.3. Analytical methods

Analytical methods were carried out on a representative sample (approximately 20 kg) obtained by mixing four sub-samples of about 5 kg each, taken from different points of the bulk material. Samples were ground to 15 mm particle size to obtain representative samples. The samples were frozen at -18 °C within 12 hours after sampling. Before each analysis samples were thawed for 24 hours at room temperature. We have recently observed that this procedure is the most adequate to preserve the samples biological activity, especially when respiration indices need to be measured after freezing (Pognani et al., 2011).

These representative samples were used to carry out all the analytical tests according to the Test Methods for the Examination of Composting and Compost (USDA, 2001): pH (Method 04.10), Total Solids (TS) (Method 03.09-A), Volatile Solids (VS) (Method 03.09-A), Total Organic Carbon (TOC) (Method 04.01-A), total Kjeldahl nitrogen (TKN) (Method

04.02-A), ammonia nitrogen N-NH_3 (measured on fresh material) (Method 04.02-B) and total nitrogen N_{tot} (TKN plus N-NH_3). In addition, the total phosphorous content (reported as P_2O_5) was measured according to APHA (1998) (Method 4500-PC) and fat content according to USEPA (1998) (Method 9071B). All tests were performed in triplicate and the results are presented as an average value followed by the corresponding standard deviation. This standard deviation corresponds to the sub-samples obtained during one year of measurements (from 4 to 5 samplings that correspond to 12 or 15 analysed sub-samples).

3. Result and discussion

3.1. General mass balance

A complete characterization of the facility in terms of TS, VS and percentage of wet matter was performed (Figure 1). The plant treated around 23000 Mg OFMSW y^{-1} in wet weight (w.w.) (TS content of 285 ± 37 g kg^{-1} w.w. and VS content of 787 ± 72 g kg^{-1} TS). This corresponded to the 89.5% of the total waste treated. The plant used a small amount (2700 Mg y^{-1}) of diatomaceous earth waste with vegetal grease from the biodiesel industry (TS of 807 ± 80 g kg^{-1} w.w. and VS of 539 ± 210 g kg^{-1} TS) as co-substrate to improve the anaerobic digestion performance (Fountoulakis and Manios, 2009; Ponsá et al., 2011). This co-substrate was characterized by a high fat content (409 ± 209 g kg^{-1} TS) and it is practically free of nitrogen and phosphorous. Diatomaceous earth waste was added to the OFMSW before the pre-treatment at a volumetric ratio of 1:10 to form the initial mixture (TS of 341 ± 26 g kg^{-1} w.w. and VS of 607 ± 164 g kg^{-1} TS) (Figure 1).

The plant has two types of rejected materials identified as the pre-treatment refuse and the compost refuse (TS of 393 ± 99 and 619 ± 4 g kg^{-1} w.w. and VS of 506 ± 24 and 345 ± 18 g kg^{-1} TS, respectively) (Figure 1, Table 1). Large wastes were manually pre-selected before disposing the initial mixture to the pre-treatment step and they were sent to other recycling facilities. Pre-treatment refuse together with the refining refuse material corresponded to 35.7% of the initial mixture (OFMSW plus diatomaceous earth) and they were disposed in a sanitary landfill.

During the anaerobic digestion step, 50.9% of the initial mixture wet matter was digested and 15.9% was transformed into biogas (4073 Mg y^{-1}). The obtained digestate was mixed with bulking agent (TS of 713 ± 81 g kg^{-1} w.w. and VS of 936 ± 3 g kg^{-1} TS) in a volumetric ratio of 1:4 (digestate/bulking agent) and composted in a tunnel composting system (5 tunnels) during 7 days. At the end of the tunnel phase, semi-composted material (TS of 558 ± 30 g kg^{-1} w.w. and VS of 426 ± 30 g kg^{-1} TS) was transferred to a maturation area to be cured for 1 to 2 weeks in turned piles. The final compost (TS of 604 ± 4 g kg^{-1} w.w. and VS 397 ± 17 g kg^{-1} TS) (Figure 1, Table 1) was treated using a trommel screen (10 mm of cut-off) to remove the residual bulking agent and residual impurities before being stocked and marketed. Bulking agent not degraded was re-utilized.

Leachate (TS of 50 ± 24 g kg^{-1} w.w. and VS of 497 ± 67 g kg^{-1} TS) was stored in the plant and transported by a tank truck to a wastewater treatment plant twice a month. Leachate generation was mainly located in the pre-treatment step, the tunnel phase, the condensates derived from the post treatment of biogas and rain that falls into the perimeter of the facility (Figure 1). 70 L of leachate per Mg of initial mixture were produced.

3.1.1. Mechanical pre-treatment mass balance

The OFMSW was transported to the plant and it was processed every day. In the discharge area, the OFMSW was mixed at volumetric ratio of 10:1 with diatomaceous earth and the initial mixture passed to the mechanical pre-treatment step, consisting of a garbage bag opener machine followed by a ballistic separator. The heavy/small fraction was mainly constituted by organic matter and continued the process to the anaerobic digestion step whereas the light/large fraction passed trough a magnetic separator to collect metals (113 Mg y^{-1}, plant manager personal communication). The rest of this fraction was rejected, constituting the refuse of the pre-treatment step. The specific distribution of wet matter in the pre-treatment step was: 32.0% of the initial wet matter was rejected in the pre-treatment step (8221 Mg y^{-1} of wet matter; 1292 Mg y^{-1} of C, 48.5 Mg y^{-1} of N_{tot} and 1.5 Mg y^{-1} of P_2O_5) (Figure 2) and 67.6% of wet matter continued to the grinder/pump system and the anaerobic digestion step. Manual characterization of the pre-treatment refuse showed an average weight composition of: 44.01% of organic fraction (including paper, carton and textile), 38.85% of inert fraction (plastic, glass and others), 7.36% of metals, 5.66% of vegetable fraction (leaves, branches and little plants) and 4.12% of bags not open (Figure 1).

The little difference between the VS value of the initial mixture and the VS value of the pre-treatment refuse sample (Figure 1), jointly with the high respirometric index (DRI_{24h} and AT_4) and ABP_{21} values (Table 1), indicated that part of the initial biodegradable organic matter was diverted to the refuse instead of being processed in further steps. Furthermore the storage time of the initial mixture and the dilution of VS due to the addition of diatomaceous earth (VS of 540 ± 21 g kg^{-1} of TS), could determine the reduction of VS indicating that the efficiency of the pre-treatment process should be improved (Pognani et al., 2010). Although there are scarce publications on the effect of the pre-treatment steps in complex waste treatment plants, these results confirm the previous observations by other authors related to the loss of biodegradable organic matter during the pre-treatment step (Muller et al., 1998; Bolzonella et al., 2006; Ponsá et al., 2010b).

During this step a considerable part of leachate was produced. Raw OFMSW presents high moisture content (typically more than 70%) and its manipulation due to the addition the diatomaceous earth and the charging operation to the bag-opener equipment caused an important loss of liquid. Unfortunately, due to the limitations of the leachate collection system design it was not possible to quantify where and how much leachate were produced and to identify the sources of the wet matter (Table 1) contained in the leachate stream.

3.1.2. Anaerobic digestion step

The organic fraction coming from the pre-treatment step moved to the grinder/pump system. The grinder reduced the particle size of the organic matter to prepare it for the anaerobic digestion and the pump mixed the fresh undigested material with the digestate to warm it up and to homogenize the input mixture prior to pump it into the digester. Water vapour was used to warm up the initial mixture by means of a heat exchanger.

The grinder had an efficiency of 98.8% (Figure 1) (plant manager personal communication). This causes a loss of 208 Mg y^{-1} of wet matter (51 Mg of C y^{-1}, 2.6 Mg of N_{tot} y^{-1} and 0.2 Mg of P_2O_5 y^{-1}) with respect to the input material to the anaerobic digestion process (17373 Mg y^{-1} of wet matter) that was daily collected during the cleaning operations of the plant and sent to landfill (Figure 2).

In the anaerobic digestion step 58.5% of the VS of the feed were converted mainly to biogas measured at normal conditions (0ºC, 1 atm) with a value of 746 Nm^3 Mg^{-1} of VS_{feed}, which is similar to those found in other studies using the OFMSW coming form a source-separated collection system (Pognani et al., 2009; Ponsá et al., 2011). The average production of biogas was estimated at 5200 Nm^3 day^{-1} and 1900000 Nm^3 y^{-1}. The biogas production was 466 Nm^3 Mg^{-1} of wet matter resulting in an output flow of 1021 Mg of C y^{-1} calculated on an average composition of biogas of 35.7% CO_2 and 64.3% CH_4 for this kind of wastes (Davidsson et al., 2007; Mata-Álvarez, 2003).

Biogas was post-treated before its utilization in co-generator units producing 46 m^3 y^{-1} of condensate (plant manager personal communication). Biogas was burned to produce electricity (sold to an electrical company) and hot water. The nitrogen content in the condensate water obtained during the post treatment of biogas could not be determined because samples were not available. In Schievano et al. (2011) it was reported that the total nitrogen content (mainly in the form of ammonia) in the biogas moisture was typically in the within the range of 2 to 3 g N_{tot} kg^{-1} of condensate.

3.1.3. Composting process and curing phase

To improve the porosity, to reduce the moisture content and to promote air circulation through the mass of the digestate, wood chips and pruning wastes were used as bulking agent and were added at a ratio of 1:4 (v:v, digestate:bulking agent) using an industrial homogenizer (Ruggieri et al., 2009). The mixture (digestate and wood chips) was aerobically decomposed in a tunnel composting system. The residence time of the tunnel phase was one week. During this phase air was provided discontinuously (4 min aeration/11 min non-aeration). The temperature of the mass was monitored to ensure its correct hygienization, which was easily achieved (data not shown). Oxygen content was also monitored and the concentration of 10% (v/v) in the outlet air was guaranteed to ensure that the process occurred under aerobic conditions (Leton and Stentiford, 1990). The excess of moisture content was collected in leachate collection pipes. At the end of the tunnel phase the semi-composted material was transferred to the curing area for 1 to 2 weeks. The curing phase was performed in piles that were turned twice a day. The objective of this last biological step was to achieve a complete biodegradation and stabilization of the remaining biodegradable organic matter and to reduce the moisture content.

As observed in Figure 1 it may appear that from anaerobic digestion to the curing phase only a reduction of 6.6% of wet matter was achieved. However, it should be considered that prior to the composting process, bulking agent was added, which increases the amount of slowly biodegradable matter. This bulking agent was separated at the final refining stage.

Other works have shown the influence of bulking agent presence in the final compost (Ruggieri et al., 2008).

An important point in the mass balance of composting is related to the gaseous emissions produced during this step. In this plant, these emissions were collected and treated by means of an acid scrubber and a biofilter system. Data on emissions from the biofilters of this plant are available in Cadena et al. (2009a).

Although NH_3 and CO_2 emissions could not be experimentally determined during the composting stage, they could be estimated from the data presented in Pognani et al. (2010). NH_3 emissions were estimated using the $N\text{-}NH_4^+$ content of the samples at the beginning (digestate, 11.0 g kg^{-1} of $N\text{-}NH_4^+$ on TS basis) and at the end (last windrow, 1.1 g kg^{-1} of $N\text{-}NH_4^+$ on TS basis including the bulking agent TS content) of the composting process. Ammonia content reduction demonstrated that during the composting phase 85% of NH_3 (calculated on TS basis) was emitted (74% on VS basis) corresponding to 9.3 Mg y^{-1} of N_{tot} on VS basis. Other works have highlighted the high ammonia emissions observed during the composting of digested materials, which it is normally due to the high content of $N\text{-}NH_4^+$ that it is produced during anaerobic digestion (Pagans et al., 2006). In this case, the average pH value of the piles was 8.7 ± 0.2, which reinforce the hypothesis that an alkaline pH provokes a high ammonia emission.

At the same time, the amount of CO_2 emissions could be estimated for the composting process from respiration data. An ultimate AT assay (AT_u, which measures de total content of biodegradable organic matter) was performed during 3 weeks. During this time the production of CO_2 was recorded and the emission of C was estimated to be in the range of 656 (for two weeks of composting process) to 956 Mg y^{-1} (for three weeks of composting process) (i.e. from 18.9 to 27.5% carbon of the initial mixture) (Table 2). It is interesting to point out that these results are similar to those found in other work using the emission of carbon dioxide to estimate the efficiency of the process (Martínez-Blanco et al., 2010). However, from the point of view of environmental impact, this carbon dioxide is not considered as greenhouse gas, as it comes from biogenic sources (Amlinger et al., 2008).

Finally, a consumption of 13.9% of wet (total) matter (3577 Mg y^{-1}) was estimated in the composting process (tunnel and curing phase) excluding the final compost refining step.

3.1.4. Compost refining phase

Composted material was screened in a 10 mm mesh trommel. The refining system separates compost from the non-degraded bulking agent (re-used) and from the residual thin inorganic material and plastic (refuse). Due to the relatively low moisture content of the organic material achieved during the curing phase (TS of 604 ± 4 g kg^{-1} w.w., Table 1) a considerable amount of compost dust was produced (1.1% of wet matter of the initial mixture; according to the plant data). During the normal cleaning operation of the facility the compost dust was collected from the ground and rejected. The compost obtained contained 27.6% of the initial mixture wet matter (specifically 842 Mg of C y^{-1}, 89.8 Mg of N_{tot} y^{-1} and 8.9 Mg of P_2O_5 y^{-1}) (Figure 2) and it was marketed and used in agriculture, since its metal content was (in mg kg^{-1}, dry basis): Ni: 96.8; Cd: 0.4; Cr: 39.0; Hg: 0.4; Cu: 99.7; Zn: 158.4 and Pb: 66.4. Some values (Ni, Cu and Pb) were slightly high than those recommended for Class A Compost according to Spanish legislation.

3.2. Evolution of respiration indices

The values of DRI_{24h}, AT_4 and ABP_{21} are presented in Table 1 and are expressed on a dry matter basis, to avoid the error related to the variation of the organic matter content as the biodegradation process occurs and because of the distortion produced by the addition of a bulking agent during the composting phase (Barrena et al., 2005; Ponsá et al., 2008; Pognani et al., 2010).

Regarding the biological process, the step where the labile organic matter was mainly consumed was the anaerobic digestion. A reduction of 74% and 85% for the initial mixture calculated on DRI_{24h} and ABP_{21} basis respectively was observed in this step. The aerobic stabilization (Table 1) from digestate to compost showed a further decrease of 78% and 74% on DRI_{24h} and AT_4 basis, respectively. ABP also showed a reduction of 61%. These results are similar to those found in other combined anaerobic/aerobic municipal waste treatment plants (Ponsá et al., 2008).

Regarding the overall efficiency of the facility, the respirometric indices (and also ABP_{21}) confirmed that a high level of stabilization was achieved and showed a high efficiency of the plant on this point. Thus, respiration indices obtained for the raw OFMSW were high (4.2 ± 1.2 g O_2 kg TS^{-1} h^{-1}) (Table 1), as expected for an organic material rich in labile organic compounds, whereas the final compost was well stabilized and showed values (0.3 ± 0.1 g O_2 kg TS^{-1} h^{-1}) that were 91% lower than that the initial mixture. This confirms the high level of efficiency of this type of plants designed for the treatment of the OFMSW. However, it must be considered that these efficiency values do not consider the refuse produced in the plant, which is around 32% of the total input mass. Thus, anaerobic digestion input showed a drop of the DRI_{24h} (2.3 ± 0.8 g O_2 kg^{-1} TS h^{-1}) that highlights the losses of labile organic matter during the pre-treatment step and the grinding process. Anaerobic digestion process determined a drop of 61% of respirometric activity (DRI_{24h} of 0.9 ± 0.1 g O_2 kg^{-1} TS h^{-1}). The composting step determined a further reduction of the 55% of DRI_{24h} (0.4 ± 0.2 g O_2 kg^{-1} TS h^{-1}). Finally, the curing phase provoked a reduction of DRI_{24h} until reaching 0.2 ± 0.1 g g O_2 kg^{-1} TS h^{-1}.

However, it is necessary to take into account that the results also indicate that the refuse from the pre-treatment has a high biological activity, which means that a large amount of organic matter suitable to produce biogas and compost is lost. In fact, the DRI_{24h} determined in this refuse is 3.4 ± 1.1 (Table 1), only 3% less than initial mixture (3.5 ± 1.4 g O_2 kg TS^{-1} h^{-1}). Considering the high production of this type of refuse and its high biological activity a post-treatment to stabilize the organic matter or, alternatively, the technical improvement of the pre-treatment step would prevent or reduce the environmental adverse effects that the direct landfilling of this refuse flow can cause (Araújo Morais et al., 2008).

In general, biological stability indices in their several forms (dynamic or cumulative, aerobic or anaerobic), were strongly recommended when the overall efficiency of a waste treatment plant had to be evaluated (Cossu and Raga, 2008, Ponsá et al., 2008). However, the content of TS and VS in each operation analysed has to be carefully considered. Since both indices (aerobic and anaerobic) presented a similar evolution through the plant, aerobic respiration indices were preferable because of the long time needed in the ABP test (Barrena et al., 2009; Scaglia et al., 2010).

3.3. Nutrient flow (C, N_{tot}, P_2O_5) and mass balance

Figure 2 shows the nutrient flows analyzed. The main amounts of N_{tot} and P_2O_5 were introduced in the facility by the OFMSW and only in a minor part by the bulking agent (5.7% of N_{tot} and 9.6% of P_2O_5). Carbon was ignored because its contribution over many cycles is considered negligible.

The main output flows of nutrients detected were the pre-treatment refuse flow, the compost flow and biogas (carbon flow). The pre-treatment refuse was constituted by 32.0% of wet matter, 37.2% of C, 28.5% of N_{tot} of and 16.7% of P_2O_5 of the initial mixture. These high percentages of this rejected fraction were lost. The biogas flow contained 38.7% of the initial carbon. The final compost (27.6% of initial mixture wet matter) contained 49.7% of the initial N_{tot} and 86.4% of the initial P_2O_5 but only 21.6% of the total carbon treated in the facility.

The global mass balance between total input and output of C, N_{tot}, P_2O_5 and wet matter is reported in Table 2. The results showed that the 16.6% of C, the 18.4% of N_{tot} and the 0.4% of wet matter were not quantified in the balance. This negative balance in C and N sources could be attributed to the emission of CO_2 and NH_3 during the composting stage. When considering the estimated emissions of NH_3 and CO_2 during the composting stage the results showed that the carbon balance fluctuate from a negative balance of 0.2% (in the case of two weeks composting process) to a positive balance of 7.9% (in case of three weeks). When estimating the ammonia emissions during the composting process a negative balance of 13.1% was estimated (Table 2). Also, denitrification may occur causing a loss of N in the form of N_2 (Sommer and Dahl, 1999). Nevertheless, it can be considered that the level of error detected is acceptable under the restrictions of the study (Cadena et al., 2009b).

Regarding P_2O_5, data showed a positive balance of 6.4% in the output flow. As seen in Figure 2 and Table 1, there was an evident P_2O_5 concentration in the final compost caused by the reduction of organic matter consumed during the biological steps of the process.

Finally it should be pointed out that the negative and positive values of the overall balances of C, N_{tot}, P_2O_5 and wet matter may be also caused by inherent difficulty of sampling in full-scale facilities. Unfortunately, we have no evidences of other studies reporting a complete balance of these elements in complex full-scale waste treatment plants.

4. Conclusions

The methodology used to assess the mass balance of this facility (express on wet matter and total quantity of C, N_{tot} and P_2O_5) has permitted to estimate the efficiency of the entire process and each treatment step. Results showed that a non-negligible part of the initial mixture wet matter was rejected and landfilled, which was specifically due to the inefficient mechanical pre-treatment step (garbage bag-opener machine and ballistic separator). The stabilization of the organic fraction was fully achieved in the final compost (DRI_{24h} of 0.3±0.1 g O_2 kg TS^{-1} h^{-1}) was categorized as very stable compost. The anaerobic digestion step was the main responsible of the reduction of the initial biodegradable matter, while the composting process reduced moisture and stabilized the waste. In the final compost (27.6% of the initial wet matter) it could be found a half of the initial N_{tot} and 86.4% of P_2O_5. This high content in nutrients and the high level of respiration stability resulted in a high-quality compost for agricultural use.

Acknowledgements

Financial support was provided by the Spanish *Ministerio de Ciencia e Innovación* (Project CTM2009-14073-C02-01). Michele Pognani has a pre-doctoral scholarship from the Spanish *Ministerio de Ciencia e Innovación* (Ref. BES-2007-17634). Raquel Barrena was supported by a *Juan de la Cierva* post-doctoral contract from the Spanish *Ministerio de Ciencia e Innovación* (Ref. JCI-2008-1989).

References

Adani, F., Lozzi, P., Genevini, P., 2001. Determination of biological stability by oxygen uptake on municipal solid waste and derived products. Compost Sci Util 9, 163-178.

Adani, F., Tambone, F., Gotti, A., 2004. Biostabilization of municipal solid waste. Waste Manage 24, 775-783.

Amlinger, F., Peyr, S., Cuhls, C., 2008. Greenhouse gas emissions from composting and mechanical biological treatment. Waste Manage Res 26, 47-60.

Ağdağ, O.N., Sponza, D.T., 2005. Co-digestion of industrial sludge with municipal solid wastes in anaerobic simulated landfilling reactors. Process Biochem 40, 1871-1879.

American Public Health Association (APHA), 1998, Standard methods for the examination of water and wastewater, 20th edition, Washington, USA, 1998.

Banks, C.J., Chesshire, M., Heaven, S., Arnold, R., 2011. Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. Bioresource Technol 102, 612-620.

Barrena, R., Vázquez, F., Gordillo, M.A., Gea, T., Sánchez, A., 2005. Respirometric assay at fixed and process temperatures to monitor composting process. Bioresource Technol 96, 1153-1159.

Barrena, R., d'Imporzano, G., Ponsá, S., Gea, T., Artola, A., Vázquez, F., Sánchez, A., Adani, F., 2009. In search of a reliable technique for the determination of the biological stability of the organic matter in the mechanical-biological treated waste. J Hazard Mater 162, 1065-1072.

Bolzonella, D., Battistoni, P., Susinii, C. and Cecchi, F., 2006. Anaerobic codigestion of waste activated sludge and OFMSW: the experiences of Viareggio and Treviso plants (Italy). Wat Sci Technol 53, 203-2011.

Cadena, E., Colón, J., Artola, A., Sanchez, A., Font, X., 2009a. Environmental impact of two aerobic composting technologies using Life Cycle Assessment. Int J LCA 14, 401-410.

Cadena, E., Colón, J., Sánchez, A., Font X., Artola, A., 2009b. A methodology to determine gaseous emissions in a composting plant. Waste Manage 29, 2799-2807.

Correia, C.N., Vaz, F., Torres, A., 2008. Anaerobic digestion of biodegradable waste - operational and stability parameters for stability control. In: 5th IWA International Symposium on Anaerobic Digestion of Solid Wastes and Energy Crops, Tunisia.

Correia, C.N., Torres, A. Vaz, F., 2007. The Characteristics of the Biodegradable Waste and the operational parameters of the anaerobic thermophilic digestion plant of Lisbon area. In: Proceedings Sardinia 2007- Eleventh International Waste Management and Landfill Symposium, Italy.

Cossu, R., Raga, R., 2008. Test methods for assessing the biological stability of biodegradable waste. Waste Manage 28, 381-388.

Davidsson, A., Gruvberger, C., Christensen, T.H., Hansen, T.L., Jansen, J.C., 2007. Methane yield in source-sorted organic fraction of municipal solid waste. Waste Manage 27, 406-414.

de Araújo Morais, J., Ducom, G., Achour. F., Rouez, M., Bayard, R., 2008. Mass balance to assess the effency of a mechanical-biological treatment. Waste Manage 28, 1791-1800.

Fountoulakis, M.S., Manios, T., 2009. Enhanced methane and hydrogen production from municipal solid waste and agro-industrial by-products co-digested with crude glycerol. Bioresource Technol 100, 3043-3047.

Leton, E.G., Stentiford, E.I., 1990. Control of aeration in static pile composting. Waste Manage Res 8, 299-306.

Martínez-Blanco, J., Colón J., Gabarrell, X., Font, X., Sánchez, A., Artola, A., Rieradevall, J., 2010. The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Manage 30, 983-994.

Mata-Álvarez, J. 2003. Biomethanization of the Organic Fraction of Municipal Solid Wastes, IWA Publishing, London. UK.

Muller, W., Fricke, K., Vogtmann, H., 1998. Biodegradation of organic matter during mechanical biological treatment of MSW. Compost Sci Util 6, 42-52.

Pagans, E., Barrena, R., Font, X., Sánchez A., 2006. Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. Chemosphere 62, 1534-1542.

Pognani, M., Barrena, R., Font, X., Scaglia, B., Adani, F., Sánchez A., 2010. Monitoring the organic matter properties in a combined anaerobic/aerobic full-scale municipal source-separated waste treatment plant. Bioresource Technol 101, 6873-6877.

Pognani, M., D'Imporzano, G., Scaglia, B., Adani, F., 2009. Substituting energy crops with organic fraction of municipal solid waste for biogas production at farm level: a full-scale plant study. Process Biochem 44, 817-821.

Pognani, M, Barrena, R., Font, X., Sánchez, A., 2011. Effect of freezing on the conservation of the biological activity of organic solid wastes. Bioresource Technol In press, available on-line: doi:10.1016/j.biortech.2011.11.097

Ponsá, S., Gea, T., Alerm, L., Cerezo, J., Sánchez, A., 2008. Comparison of aerobic and anaerobic stability indices through a MSW biological treatment process. Waste Manage 28, 2735-2742.

Ponsá, S., Gea, T., Sánchez, A., 2010a. Different indices to express biodegradability in organic solid wastes. J Environ Qual 39, 706-712.

Ponsá, S., Gea, T., Sánchez, A., 2010b. The effect of storage and mechanical pretreatment on the biological stability of municipal solid wastes. Waste Manage. 30, 441-445.

Ponsá, S., Gea, T., Sánchez, A., 2011. Anaerobic co-digestion of the organic fraction of municipal solid waste with several pure organic co-substrates. Biosystems Eng 108, 352-360.

Ruggieri, L., Gea, T., Mompeó, M., Sayara, T., Sánchez, A., 2008. Performance of different systems for the composting of the source-selected organic fraction of municipal solid waste. Biosystems Eng 101, 78-86.

Ruggieri, L., Gea, T., Artola, A., Sánchez, A., 2009. Air filled porosity measurements by air pycnometry in the composting process: a review and a correlation analysis. Bioresource Technol 100, 2655-2666.

Scaglia, B., Confalonieri, R., D'Imporzano, G., Adani, F., 2010. Estimating biogas production of biologically treated municipal solid waste. Bioresource Technol 101, 945-952.

Schievano, A., D'Imporzano, G., Salati, S., Adani, F., 2011. On-field study of anaerobic digestion full-scale plants (Part I): an on-field methodology to determine mass, carbon and nutrients balance. Bioresource Technol, submitted.

Sommer, G.S., Dahl, P., 1999. Nutrient and carbon balance during the composting of deep litter. J Agr Eng Res 74, 145-153.

The U.S. Department of Agriculture and The U.S. Composting Council, 2001. Test Methods for the Examination of Composting and Compost. Edaphos Int, Houston, USA.

The US Environmental Protection Agency, 1998. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods. Available on-line: http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/9071b.pdf (accessed December 2011).

Vaz, F., Torres, A., Correia, C.N, 2008. Case study: the characteristics of the biodegradable waste for the anaerobic digestion plant in Lisbon area. Wat Sci Technol 58, 1563-1568.

Tables:

Table 1: Chemical and respirometric characterization of waste samples.

Sample	**pH**	**TS (g kg ww^{-1})**	**VS (g kg TS^{-1})**	**TOC (g kg TS^{-1})**	**N-NH$_3$ (g kg TS^{-1})**	**TKN (g kg TS^{-1})**	**N$_{tot}$ (g kg TS^{-1})**	**P$_2$O$_5$ (g kg TS^{-1})**	**DRI$_{24h}$ (g O$_2$ kg TS^{-1}h^{-1})**	**AT$_4$ (g O$_2$ kg TS^{-1}h^{-1})**	**ABP$_{21}$ (NL kg TS^{-1})**
OFMSW	5.3 ± 0.6	285 ± 37	787 ± 72	420 ± 18	0.6 ± 0.2	25 ± 2	26 ± 2	1.37 ± 0.08	4.3 ± 1.2	295 ± 117	403 ± 7
Diatomaceous earth	4.3 ± 1.3	807 ± 80	539 ± 210	330 ± 131	not detected	not detected	not detected	0.19 ± 0.04	0.15 ± 0.1	12 ± 1	620 ± 75
Bulking agent	6.4 ± 0.1	713 ± 81	936 ± 3	334 ± 10	not detected	8 ± 1	8 ± 1	0.70 ± 0.01	not determined	not determined	not determined
Pretreatment refuse	5.7 ± 0.6	393 ± 99	506 ± 24	400 ± 68	1.8 ± 0.2	13 ± 7	15 ± 8	0.46 ± 0.01	3.5 ± 1.1	259 ± 40	349 ± 60
Refining refuse	8.7 ± 0.1	619 ± 4	345 ± 18	168 ± 6	3.0 ± 0.1	14 ± 2	16 ± 1	2.05 ± 0.03	0.3 ± 0.1	12 ± 3	22 ± 5
Final compost	8.6 ± 0.1	604 ± 4	397 ± 17	197 ± 27	2.9 ± 0.8	19 ± 3	21 ± 4	2.09 ± 0.04	0.3 ± 0.1	23 ± 11	26 ± 9
Leachate	6.8 ± 0.3	50 ± 24	497 ± 67	288 ± 55	27.2 ± 15.7	24 ± 4	51 ± 28	1.03 ± 0.01	not determined	not determined	not determined

Abbreviations: OFMSW: organic fraction of municipal solid waste; TS: Total Solids; VS: Volatile Solids; TOC: Total Organic Carbon; TKN: total Kjeldahl nitrogen; N$_{tot}$: Total nitrogen; ABP: anaerobic biogas potential; DRI$_{24h}$: dynamic respiration index (24 hours); AT$_4$: cumulative respiration index (4 days).

Table 2: Nutrients (C, N_{tot} and P_2O_5) and wet matter (WM) mass balance. Bulking agent carbon was ignored in WM balance because its contribution over many cycles is considered negligible.

	Input ($Mg\ y^{-1}$)	**Output ($Mg\ y^{-1}$)**	**Estimated Emissions ($Mg\ y^{-1}$)**	**Balance (%)**	**Balance (with estimated emissions) (%)**
C	3901	3254	656 to 956	- 16.6	- 0.2 to + 7.9
N_{tot}	181	148	9.3	- 18.4	- 13.1
P_2O_5	10.3	11.0	/	+ 6.4	/
WM	25700	25809	/	+ 0.4	/

Abbreviations: C: carbon; N_{tot}: total nitrogen; P_2O_5: phosphorous; WM: wet matter.

Captions to figures

Figure 1: Scheme of the waste treatment plant including the materials flow and characterization. Values shown correspond to the characterization of the input material to each step. Calculations are made on the basis of the treatment of 100 kg of initial mixture. Characterization of pre-treatment refuse is also presented. Solid line corresponds to solid waste and dot line corresponds to liquid streams. (*) Rain that falls into the plant perimeter contributed to the generation of leachate. Abbreviations: OFMSW: organic fraction of municipal solid waste; TS: total solid; VS: volatile solid.

Figure 2: Nutrient (C, N_{tot} and P_2O_5) and wet matter flows in the studied plant during a year. Abbreviations: OFMSW: organic fraction of municipal solid waste; WM: wet matter; C: carbon; N_{tot}: total nitrogen; P_2O_5: phosphorous; WWTP: waste water treatment plant.

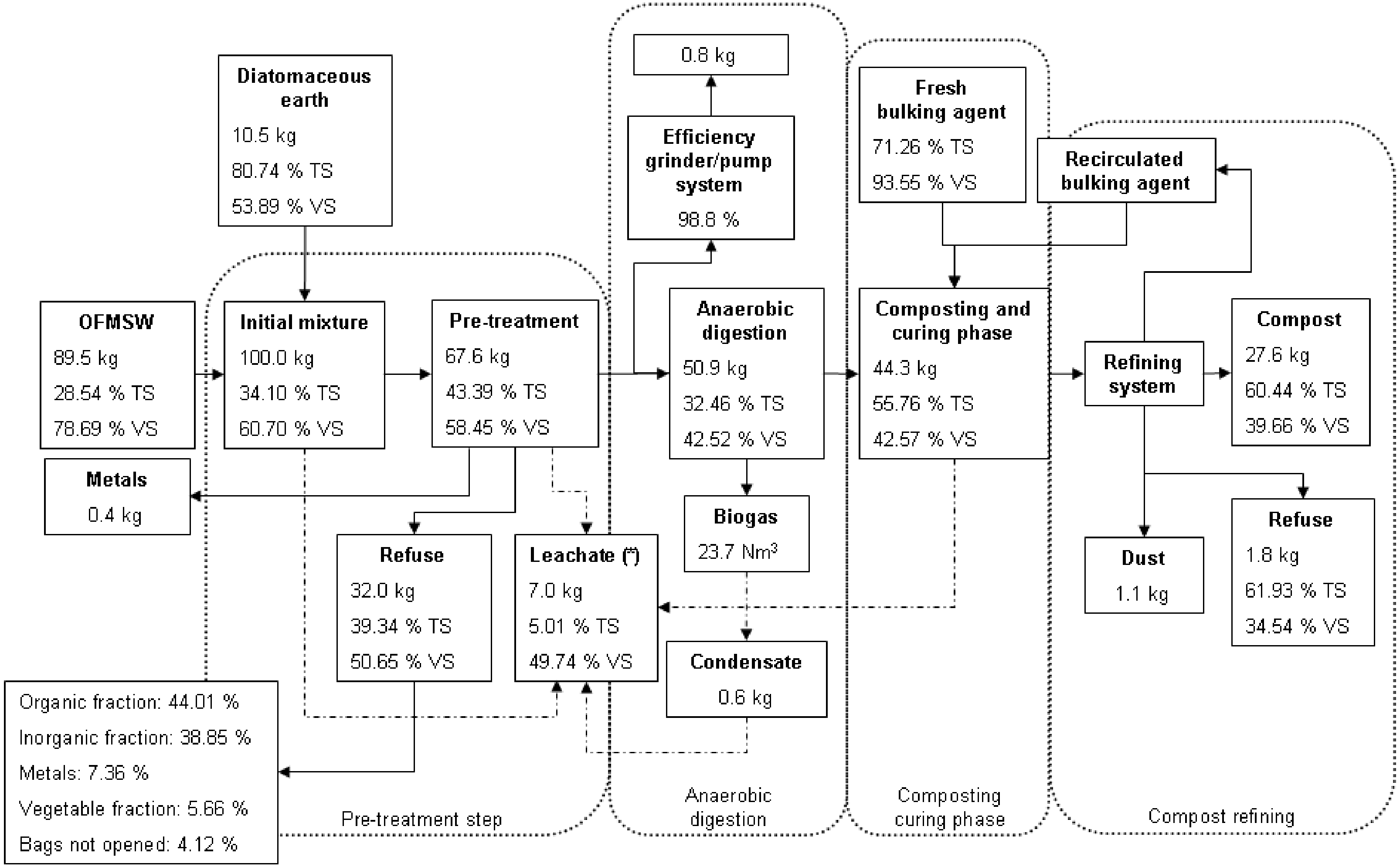
Diatomaceous earth
10.5 kg
80.74 % TS
53.89 % VS
OFMSW
89.5 kg
28.54 % TS
78.69 % VS
Initial mixture
100.0 kg
34.10 % TS
60.70 % VS
Pre-treatment
67.6 kg
43.39 % TS
58.45 % VS
Metals
0.4 kg
Refuse
32.0 kg
39.34 % TS
50.65 % VS
Leachate (*)
7.0 kg
5.01 % TS
49.74 % VS
Organic fraction: 44.01 %
Inorganic fraction: 38.85 %
Metals: 7.36 %
Vegetable fraction: 5.66 %
Bags not opened: 4.12 %
Pre-treatment step
0.8 kg
Efficiency grinder/pump system
98.8 %
Anaerobic digestion
50.9 kg
32.46 % TS
42.52 % VS
Biogas
23.7 Nm³
Condensate
0.6 kg
Anaerobic digestion
Fresh bulking agent
71.26 % TS
93.55 % VS
Recirculated bulking agent
Composting and curing phase
44.3 kg
55.76 % TS
42.57 % VS
Composting curing phase
Refining system
Compost
27.6 kg
60.44 % TS
39.66 % VS
Dust
1.1 kg
Refuse
1.8 kg
61.93 % TS
34.54 % VS
Compost refining

Figure 1

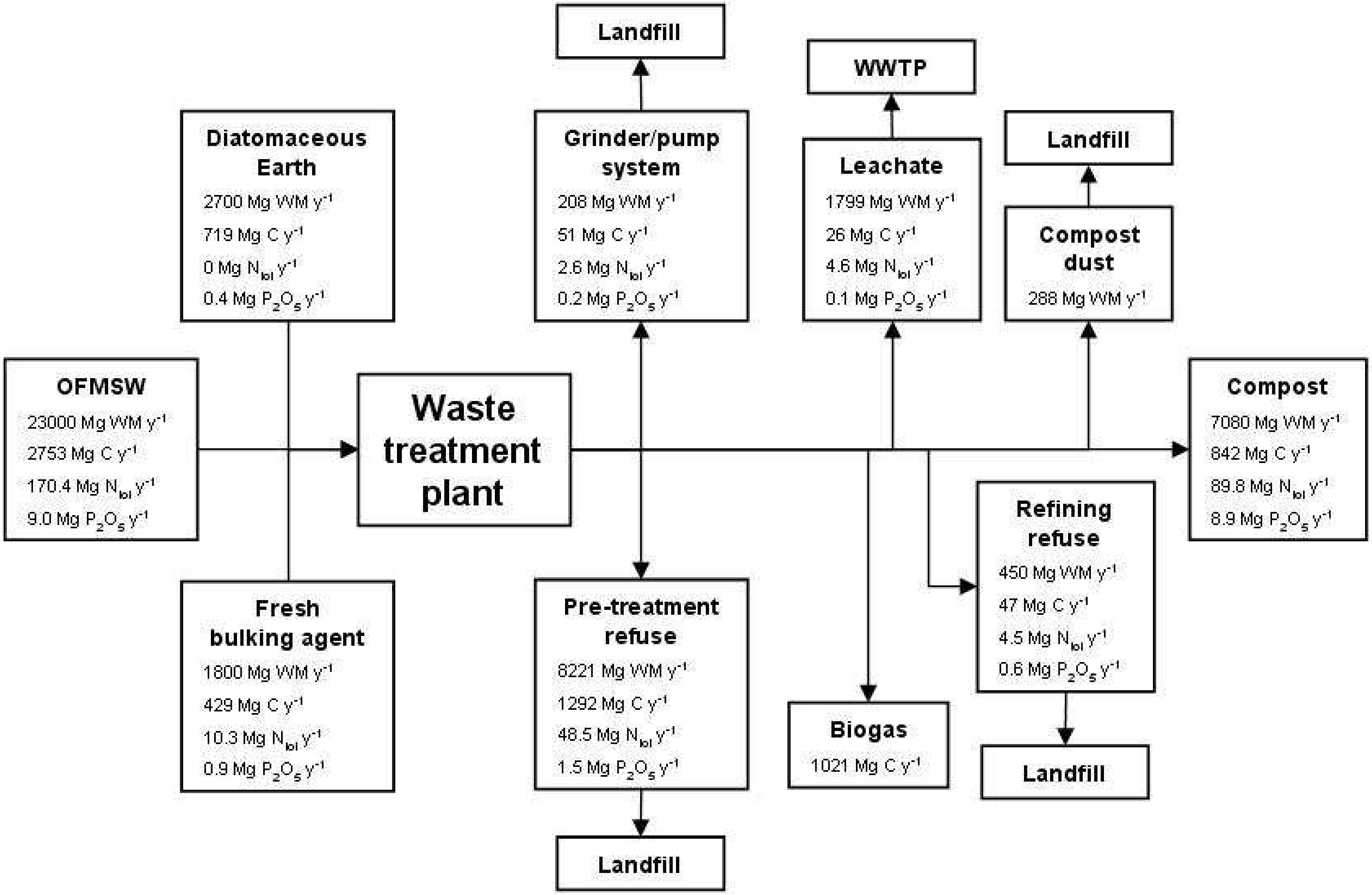
Landfill
WWTP
Diatomaceous Earth
2700 Mg WM y^{-1}
719 Mg C y^{-1}
0 Mg N_{tot} y^{-1}
0.4 Mg P_2O_5 y^{-1}
Grinder/pump system
208 Mg WM y^{-1}
51 Mg C y^{-1}
2.6 Mg N_{tot} y^{-1}
0.2 Mg P_2O_5 y^{-1}
Leachate
1799 Mg WM y^{-1}
26 Mg C y^{-1}
4.6 Mg N_{tot} y^{-1}
0.1 Mg P_2O_5 y^{-1}
Landfill
Compost dust
288 Mg WM y^{-1}
OFMSW
23000 Mg WM y^{-1}
2753 Mg C y^{-1}
170.4 Mg N_{tot} y^{-1}
9.0 Mg P_2O_5 y^{-1}
Waste treatment plant
Compost
7080 Mg WM y^{-1}
842 Mg C y^{-1}
89.8 Mg N_{tot} y^{-1}
8.9 Mg P_2O_5 y^{-1}
Refining refuse
450 Mg WM y^{-1}
47 Mg C y^{-1}
4.5 Mg N_{tot} y^{-1}
0.6 Mg P_2O_5 y^{-1}
Fresh bulking agent
1800 Mg WM y^{-1}
429 Mg C y^{-1}
10.3 Mg N_{tot} y^{-1}
0.9 Mg P_2O_5 y^{-1}
Pre-treatment refuse
8221 Mg WM y^{-1}
1292 Mg C y^{-1}
48.5 Mg N_{tot} y^{-1}
1.5 Mg P_2O_5 y^{-1}
Biogas
1021 Mg C y^{-1}
Landfill
Landfill

Figure 2