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Review

Assessment of the effectiveness of an industrial unit of mechanical–biological treatment of municipal solid waste

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ABSTRACT

An assessment of the French municipal solid waste (MSW) mechanical–biological treatment (MBT) unit of Mende was performed in terms of mass reduction, biogas emissions reduction and biostability of the biologically treated waste. The MBT unit consists of mechanical sorting operations, an aerobic rotating bioreactor, forced-aeration process in open-air tunnels (stabilization), ripening platforms and a sanitary landfill site for waste disposal in separated cells. On the overall plant, results showed a dry matter reduction of 18.9% and an oxidative organic matter reduction of 39.0%. A 46.2% biogas production decrease could also be observed. Concerning the biotreatment steps, high reductions were observed: 88.1% decrease of biogas potential and 57.7% decrease of oxidative organic matter content. Nevertheless, the usually considered stabilization indices (biogas potential, respirometric index) remained higher than recommended by the German or Austrian regulation for landfilling. Mass balance performed on each step of the treatment line showed that several stages needed improvement (especially mechanical sorting operations) as several waste fractions containing potentially biodegradable matter were landfilled with very few or no biological treatment.

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1. Introduction

The EU Landfill Directive of April 1999 (99/31/EC) sets the requirements for waste landfilling and the stepwise reduction of biodegradable organic matter from residual municipal solid waste (MSW) prior to landfilling. Member states have to develop strategies to ensure the progressive reduction over a 15-year period down to only 35% of the 1995 production. The objective is to reduce the need for landfill space, to limit biogas and leachate emissions, and to reduce the post-closure management time. The French regulation (adopted on 9th September, 1997 and modified on 19th January, 2006) imposes the recovery and treatment of the produced leachate and biogas during site exploitation and post-closure exploitation (30 years). According to this regulatory context, several strategies have been developed. In France, incineration (43%, w/w, of MSW in 2004), source separation for recycling (13%, w/w) and composting of organic fractions of MSW (6%, w/w) are the main strategies to minimize landfilling (38%, w/w). Considering the strong use of incineration for residual MSW, France has already achieved the objective of the Landfill Directive. Nevertheless, mostly because of its more positive public acceptance, mechanical–biological treatment (MBT) has been recently considered as an alternative to residual MSW incineration. At the present time, six full-scale plants are in operation and numerous projects are under development. Firstly developed in Austria and Germany, the aim of MBT is to minimize biogas and leachate productions, reduce odors during the waste deposit operations, reduce landfill settlement, and reduce the duration of the landfill site aftercare [1,2]. MBT can also be considered as a pretreatment to improve the beginning of biogas production [3]. MBT of residual MSW include: (i) mechanical pre-processing stages to sort out recyclable materials such as paper, metals and plastics, and (ii) biological stages to reduce and stabilize the biodegradable organic matter under controlled anaerobic and/or aerobic conditions.

The use of indicators of waste biological stability is a subject of interest for many researchers to predict potential environmental impacts and the behavior of waste in landfills [4–13]. The knowledge of the organic matter contained in leachates could for instance be used as an indicator of waste degradation [9,14,15]. Austria and Germany have already set limit values for the landfilling of biologically treated waste [4]. Some of these indicators are global parameters such as the calorific value ($H_0 \leq 6000\,\mathrm{kJ\,kg\,DM^{-1}}$), the total organic carbon content ($[\mathrm{TOC}]_{\mathrm{DM}} \leq 18\%$), and the total organic carbon content in eluate after a leaching procedure ($[\mathrm{TOC}]_{\mathrm{eluate}} \leq 250\,\mathrm{mg\,L^{-1}}$). Biological stability tests have been proposed to measure the biological reactivity. The most frequently used indicators of biostability are the respirometric index (RI) and the biogas potential (BP). In Germany and Austria, the reference RI test is the “Atmungsaktivität” with 4 days of aerobic incubation ($\mathrm{AT_4} \leq 5$ or $7\,\mathrm{g\,O_2\,kg\,DM^{-1}}$, respectively for Germany and Austria). More recently, a dynamic respiration index ($\mathrm{DRI} \leq 1000\,\mathrm{mg\,O_2\,kg\,VS^{-1}\,h^{-1}}$) test has been developed in Italy by Adani et al. [6] according to the Italian rules for biologically treated waste disposal in landfill [16]. The biological stability of the waste can also be measured with BP tests, corresponding to the measurement of biogas production under controlled anaerobic conditions. The most common procedure is the “Gasbildung” $\mathrm{GB_{21}}$ test, designed to measure biogas production over 21 days after the lag period, with a limit value of $20\,\mathrm{NL\,kg\,DM^{-1}}$ [17].

In France, no stability criteria have been defined for the admission of residual MSW into landfills. However, the performance of MBT in terms of mass reduction and stabilization has to be considered in order to estimate the benefit of the pretreatment prior to landfilling. In 2004, the French Environmental Agency ADEME launched a research project to study the effect of MBT on the behavior of MSW in landfills. A previous paper reported a 1-year study of the MBT process in a waste treatment plant located in Mende, France [18]. This plant was the first industrial plant operated in France for MBT before landfilling. It has been in operation since 2003. The performance has been assessed by a mass balance on each specific treatment step and on the whole plant. The present paper reports complementary data after the two waste sampling campaigns performed in September 2004 and March 2005. A particular attention has been paid to the organic carbon balance and the reduction of biogas and bio-methane potentials.

2. Materials and methods

2.1. Description of industrial MBT unit

The investigated MBT plant is located in the suburb of Mende, Lozère, France. It has been designed to treat residual MSW collected in the district of Lozère and landfill the stabilized waste. Its treatment capacity is 25 000 t of MSW/year. The unit has been described in details by de Araújo Morais et al. [18], and a synopsis is shown in Fig. 1. The residual MSW is mechanically pretreated by a rotary sieve (sieve #1) equipped with knives to tear the waste bags open and two series of holes of diameters: 70 and 450 mm. The oversize fraction (>450 mm), called CFS1 (coarse fraction from sieve #1) is directly landfilled in a specific cell (cell #3). The undersize fraction (<70 mm) called FFS1 (fine fraction from sieve #1) is sent to the biological treatment platform for stabilization and ripening. The intermediate fraction (70–450 mm) called IFS1 (intermediate fraction from sieve #1) is conveyed to a 28 m aerobic rotating bioreactor (ARB) where the waste is mixed and the easily biodegradable organic matter is aerobically degraded with a residence time of 2 days. In the ARB, moisture is controlled through the addition of leachate from the landfill; this is specific to the studied plant, as MBT plants are not always coupled with a landfill. The waste is then transferred to a second rotary sieve (sieve #2) with a sieve size of 50 mm, to remove materials >50 mm. Ferrous metals are recovered from the fraction above 50 mm by an overband magnetic separator. Finally, materials >50 mm from sieve #2, without ferrous metals and called BFS2 (baled fraction from sieve #2) are baled and landfilled in a specific cell (cell #2). The fraction <50 mm, called FFS2 (fine fraction from sieve #2) is sent to the biological treatment platform.

The two fine fractions from the pre-processing stage, FFS1 (<70 mm) and FFS2 (<50 mm) are daily sent to the stabilization section of the plant and biotreated separately. The biotreatment consists of an intensive aerobic process (hot fermentation) in open-air tunnels with forced aeration and a residence time of 6 weeks, and a maturation stage with a passive aeration and an average residence time of 15 weeks. Forced aeration is provided using drains disposed at the bottom of the windrows with an alterna-

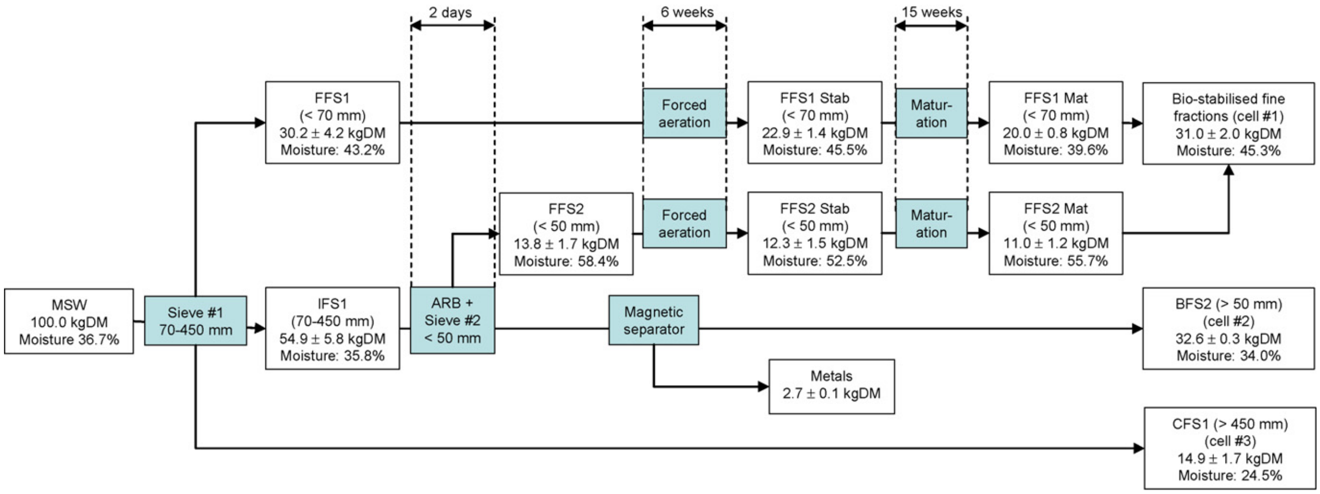

Fig. 1. Global dry mass balance over the MBT and landfill plants of Mende, Lozère, France. ARB: aerobic rotating bioreactor; MSW: municipal solid waste; FFS1: fine fraction from sieve #1; IFS1: intermediate fraction from sieve #1; CFS1: coarse fraction from sieve #1; FFS2: fine fraction from sieve #2; BFS2: baled fraction from sieve #2. Stab: after the stabilization (forced aeration) step; Mat: after the maturation step. Moisture content in % w/w.

tive aspiration/blowing regime. Waste is mechanically transferred from one tunnel to another every 2 weeks to allow homogenization and improve aeration. After 6 weeks, the two fine fractions called $FFS1_{Stab}$ and $FFS2_{Stab}$ are separately transferred to an outdoor platform for ripening with passive aeration and no mixing. After 15 weeks of maturation, the fine fractions called $FFS1_{Mat}$ and $FFS2_{Mat}$ are landfilled together in a specific landfill cell (cell #1, Fig. 1).

2.2. Waste sampling and characterization

Two sampling campaigns were carried out in September 2004 and March 2005 over 1 week each time. In this study, waste sampling was performed according to the French standard procedure XP X30-408 [19]. Sample preparation was detailed previously [18]. Six fractions were collected for characterization: input MSW, fine fractions FFS1 and FFS2, coarse fraction CFS1 and intermediate fraction IFS1 from sieve #1, and baled fraction BFS2 at the outlet of sieve #2. The collection of aerobically stabilized fractions $FFS1_{Stab}$ and $FFS2_{Stab}$ was done 6 weeks later, during the transfer from the forced-aeration stage to the maturation stage. Similarly, maturated fractions $FFS1_{Mat}$ and $FFS2_{Mat}$ were sampled during the transfer from the maturation platform to the landfill cell #1. Table 1 sums up the performed analysis and the waste on which they were conducted.

2.2.1. Solid waste component materials separation (MODECOM^{TM} procedure)

MSW (inlet), FFS1, FFS2, CFS1, IFS1, and BFS2 were characterized according to the French standard procedure XP X30-408 [19] also called the MODECOM^{TM} procedure. This manual sorting methodology results in the classification of waste materials in 13 main categories: putrescible waste (domestic green and food wastes), fine elements (<20 mm) (mainly putrescible), papers, cardboards, textiles, sanitary textiles, plastics, composite materials, unclassified combustible materials, glass, metals, unclassified non-combustible materials, and hazardous domestic waste.

2.2.2. Solid waste chemical characterization

For the fine fractions (FFS1, FFS2, $FFS1_{Stab}$, $FFS2_{Stab}$, $FFS1_{Mat}$ and $FFS2_{Mat}$), the initial dry matter (DM) and moisture contents were determined following the standard procedure NF ISO 11465 [20] by drying the sample (100 g wet matter (WM)) at 105 °C until constant weight. For the heterogeneous coarse fractions (MSW, CFS1, IFS1 and BFS2), the DM content was measured separately on each category of materials defined by the MODECOM^{TM} procedure (Section 2.2.1) by weighing a 150 kg moist sample, drying the sample at 70 °C in an oven (1 week) and weighing it again.

The volatile solids (VS) content, determined on 50 g dried samples by ignition loss at 550 °C for 4 h [21] was used to estimate the total organic content, including natural organic matter and plastics. For the coarse fractions, VS determination was carried out on reconstituted samples, as explained previously [18].

Potentially degradable organic matter was estimated through the measurement of the oxidative organic matter (OOM), consisting in the oxidation of dried samples (100 g DM) by a $7.0 \pm 0.4\,\mathrm{mol\,L^{-1}}$ solution of sodium hypochlorite at $22 \pm 2\,^{\circ}\mathrm{C}$, according to the standard procedure AFNOR XP U44-164 [22]. Three successive oxidation/washing/drying cycles were carried out, and the OOM content was calculated as the weight loss between initial and final dry masses. For the coarse fractions, OOM determination was carried out on reconstituted samples [18].

Total organic carbon concentrations TOC_{DM} were determined on dried samples using an OI Analytical^{TM} TOC analyzer, according to standard procedures [23]. Samples were previously ground to a particle size below 2 mm in a cutting mill Retsch^{TM} SM 2000. As it is difficult to obtain representative values of TOC_{DM}, measurements were repeated to obtain three acceptable values (standard deviation inferior to 5%). For the coarse fractions, TOC_{DM} of the waste mix was estimated from the TOC_{DM} content of each category determined during the latest French national campaign of waste characterization [24].

All analyses were performed in triplicate except for the determination of dry matter on coarse fractions.

2.2.3. Solid waste biological stability characterization: biogas potential (BP) and bio-methane potential (BMP)

Description of the test method for the determination of BP and BMP was provided by several authors [25–29]. Preliminary experiments on similar waste showed that 90 days of incubation at 35 °C, after the lag period, was sufficient to insure the total gas production expression. BP and BMP were determined on fine fractions FFS1, FFS2, $FFS1_{Stab}$, $FFS2_{Stab}$, $FFS1_{Mat}$ and $FFS2_{Mat}$ following a standard procedure. Dried waste samples (10 g DM) ground to 1 mm and 1 L of nutrient medium prepared according to ISO 11734 [30] were introduced into 2 L glass bottles. The inoculum was obtained from an industrial anaerobic digester treating sludge from a municipal wastewater treatment plant, and incubated in the laboratory

Table 1
Waste analysis summary.

Fractions	MSW (input)	CFS1 (reject)	IFS1	BFS2 (bales)	FFS1	$FFS1_{Stab}$	$FFS1_{Mat}$	FFS2	$FFS2_{Stab}$	$FFS2_{Mat}$
MODECOM™	x	x	x	x	x	nd	nd	x	nd	nd
DM	x[a]	x[a]	x[a]	x[a]	x	x	x	x	x	x
VS	x[b]	x[b]	x[b]	x[b]	x	x	x	x	x	x
OOM	x[b]	x[b]	x[b]	x[b]	x	x	x	x	x	x
TOC_{DM}	e[c]	e[c]	e[c]	e[c]	x	x	x	x	x	x
BP_{90}, BMP_{90}	x[a]	x[a]	x[a]	x[a]	x	x	x	x	x	x
RI_4	nd	nd	nd	nd	x	x	x	x	x	x
SHC_{10}	nd	nd	nd	nd	x	x	x	x	x	x

nd: not determined.

[a] Determined on each MODECOM™ category and calculated in proportion to the mass fraction.

[b] Determined on reconstituted samples [18].

[c] Estimated from the TOC_{DM} content of each MODECOM™ category.

[31]. The bottles were then flushed with nitrogen for a few minutes before the introduction of 100 mL of inoculum. Blanks in which no waste samples were introduced were prepared using the same procedure to evaluate the endogenous biogas production of the inoculum. Test and blank bottles were closed with air-tight rubber stoppers and plastic seals [32,33] and incubated in the dark at 35 °C. They were manually shaken every day. All tests and blanks were carried out in triplicates. Biogas production was monitored using a Digitron 2085P pressure transducer with BD Microlance needles. The biogas was discharged regularly to prevent pressure to exceed 2000 mbar (pressure transducer limit). Volumetric gas productions were calculated using the ideal gas relationship and expressed under the normal conditions of temperature (0 °C) and pressure (1 atm). Gas composition was periodically analyzed with an Agilent gas micro-chromatograph with thermal conductivity detectors and equipped with a Poraplot U column for CO_2 separation and a Molsieve one for O_2, N_2, and CH_4. Due to their heterogeneity, coarse fractions were not incubated as such. BP and BMP were determined experimentally, using the same protocol, on the different categories of materials containing potentially biodegradable organic matter, namely putrescible waste, fine elements, papers, cardboards, composite materials, textiles, sanitary textiles and unclassified combustible materials [31]. BP and BMP of coarse fractions were finally calculated by adding the biogas produced by each individual category in proportion to their mass in the waste fraction.

2.2.4. *Solid waste biological stability characterization: respiration index RI_4*

The RI_4 test consists in the determination of the oxygen consumption over 4 days of incubation at 20 °C [34]. 20 g moist waste (ground to 10 mm) was directly placed into a 2 L jar and water was added until reaching the water field capacity of the solid waste (Table 3). OXITOP® kit was used to monitor oxygen consumption. Incubation jars were hermetically closed by a manometer head to monitor pressure changes inside the bottles. Carbon dioxide produced by organic matter biodegradation was trapped by a sodium hydroxide solution placed in a beaker inside the bottle. Consequently, the recorded pressure decreased proportionally to the consumed oxygen and was subsequently converted into oxygen consumption. The bottles were incubated in triplicate in the dark at 20 °C. They were opened daily to renew air in the headspace and thus avoid oxygen limitations. As recommended by Binner et al. [4], the monitoring period has to begin after the lag phase. Results from the RI_4 test were expressed as g of consumed O_2 per kg of dry matter in 4 days of incubation.

2.2.5. *Self-heating capacity SHC_{10}*

The self-heating capacity was determined following the procedure described by Brinton et al. [35] to estimate the stability of fine fractions before and after the treatment. Waste samples (1.5 L moist samples) were introduced into Dewar adiabatic reactors and the temperature rise due to the aerobic oxidation of the organic matter was recorded over 10 days and compared to the outside temperature. Waste was previously ground to a particle size below 10 mm and water was added until reaching the waste water field capacity. This test is commonly used to quantify compost maturity grade, with a range from I (fresh material) to V (compost completely mature).

2.3. *Mass balance*

Mass balance from the results of the September 2004 campaign was reported in a previous paper [18]. The same approach was followed for the second campaign of March 2005. Results from the two campaigns were considered to calculate average values and standard deviations. The initial mass of waste (input residual MSW) considered to establish mass balances was 864 t (WM) for the first campaign and 563 t (WM) for the second one. Mass balance was calculated in terms of DM, VS, TOC_{DM}, OOM, BP and BMP at the different stages of the process, and used to evaluate the efficiency of sieving operations and biotreatments. Leachate addition was not taken into account in the mass balances as few leachate was added and organic matter from leachate was negligible. Fig. 1 presents the average data of the two campaigns for the dry matter balance.

3. Results

3.1. *Composition of waste fractions*

3.1.1. *DM, TOC_{DM} and BP distribution in the different categories of materials in the initial MSW (MODECOM™ procedure)*

On a dry mass basis, the MSW received for treatment on the plant was composed of 9% of putrescible waste, 21% of fines (<20 mm) (mainly putrescible), 15% of plastic materials, and 23% of papers and cardboards (Table 2). The high content in plastic materials, papers and cardboards was characteristic of the local situation where MSW was collected with source separation of glass and cumbersome waste only (there was no source separation of plastics and papers or cardboards).

As concerns the TOC_{DM} distribution, it can be seen that plastics accounted for 25% of the TOC_{DM} in the initial MSW. The potentially biodegradable materials, namely putrescible waste, fine particles, papers, cardboards, textiles, sanitary textiles, composite materials, and unclassified combustible materials altogether accounted for the remaining 75% of the TOC_{DM} content, with a respective distribution of 10%, 13%, 16%, 11%, 4%, 11%, 5% and 5%. Papers and cardboards accounted for 27% of the TOC_{DM}; although potentially biodegradable, they are known to exhibit relatively slow patterns of biodegradation kinetics under aerobic conditions [36]. These two categories may therefore have a strong influence on the per-

Table 2

Distribution according to the 13 categories of materials (French standard procedure AFNOR, XP X30-408 [19]). (i) Of dry matter, total organic carbon (TOC$_{DM}$) and biogas potential (BP) in the MSW (inlet) received on the plant, (ii) of dry matter and biogas potential in the coarse fraction CFS1 (>450 mm) after sieve #1 (to be landfilled in cell #3) and in BFS2 fraction (50–450 mm) after sieve #2 and after the overband (to be baled and landfilled in cell #2), and (iii) of dry matter in the IFS1, FFS1 and FFS2 fractions, according to the 13 categories of materials.

Categories	MSW (inlet)					
	Ave. (%DM)	SD (%DM)	Ave. (%TOC$_{DM}$)	SD (%TOC$_{DM}$)	Ave. (%BP)	SD (%BP)
Putrescible waste	9.1	2.5	9.9	2.8	9.2	2.6
Fines (<20 mm)	20.5	2.0	13.3	1.4	26.2	2.8
Papers	13.5	1.8	15.5	2.0	19.8	2.5
Cardboards	9.8	0.5	10.8	0.6	15.9	0.9
Textiles	3.2	0.1	4.3	0.1	7.3	0.1
Sanitary textiles	8.4	1.5	11.1	2.0	16.6	2.9
Plastics	14.8	0.2	25.6	0.2	0.0	0.0
Composites	3.6	0.6	4.6	0.8	4.3	0.7
Unclassified combustibles	3.7	0.3	4.6	0.4	0.7	0.1
Glass	4.2	0.6	0.0	0.0	0.0	0.0
Metals	5.4	1.1	0.0	0.0	0.0	0.0
Unclassified inert materials	2.9	0.4	0.1	0.0	0.0	0.0
Hazardous domestic waste	1.1	0.2	0.0	0.0	0.0	0.0

Categories	CFS1				BFS2			
	Ave. (%DM)	SD (%DM)	Ave. (%BP)	SD (%BP)	Ave. (%DM)	SD (%DM)	Ave. (%BP)	SD (%BP)
Putrescible waste	3.3	0.0	3.2	0.2	3.6	1.0	4.1	0.8
Fines (<20 mm)	6.0	3.1	7.3	4.5	1.4	0.4	2.1	0.5
Papers	13.0	0.7	18.2	2.1	22.8	0.9	38.6	5.4
Cardboards	25.0	7.3	38.8	9.6	5.8	2.5	10.9	4.1
Textiles	7.7	1.4	16.6	4.2	4.9	0.2	13.0	0.7
Sanitary textiles	5.1	2.2	9.6	3.8	8.5	1.4	19.5	1.6
Plastics	23.9	1.7	0.0	0.0	29.0	1.5	0.0	0.0
Composites	4.9	1.4	5.6	2.1	7.6	0.3	10.5	0.6
Unclassified combustibles	3.8	1.0	0.7	0.2	6.1	0.5	1.4	0.3
Glass	0.9	0.2	0.0	0.0	0.3	0.0	0.0	0.0
Metals	3.9	0.4	0.0	0.0	7.5	3.6	0.0	0.0
Unclassified inert materials	1.0	0.8	0.0	0.0	1.6	0.2	0.0	0.0
Hazardous domestic waste	1.5	0.1	0.0	0.0	0.8	0.4	0.0	0.0

Categories	IFS1		FFS1		FFS2	
	Ave. (%DM)	SD (%DM)	Ave. (%DM)	SD (%DM)	Ave. (%DM)	SD (%DM)
Putrescible waste	10.0	3.9	11.0	1.5	2.6	1.4
Fines (<20 mm)	5.2	1.2	55.9	0.8	68.3	12.9
Papers	20.1	1.8	1.4	0.6	5.9	0.3
Cardboards	10.1	1.0	1.0	0.2	2.9	1.1
Textiles	3.6	0.3	0.5	0.1	0.1	0.1
Sanitary textiles	11.8	1.5	3.6	1.8	6.4	4.3
Plastics	18.4	1.1	4.0	0.0	4.2	1.1
Composites	4.4	0.6	1.3	0.2	1.2	0.9
Unclassified combustibles	4.4	0.6	2.5	0.5	1.2	0.3
Glass	1.6	0.5	10.5	2.4	3.2	1.6
Metals	7.6	1.5	1.7	0.2	2.7	1.8
Unclassified inert materials	1.5	0.5	6.0	2.0	0.9	0.1
Hazardous domestic waste	1.2	0.4	0.6	0.0	0.4	0.2

DM: dry matter; TOC$_{DM}$: total organic carbon; BP: biogas potential; Ave.: average results; SD: standard deviation; IFS1: intermediate fraction from sieve #1; FFS1: fine fraction from sieve #1; FFS2: fine fraction from sieve #2.

formance of biodegradation at both forced aeration and ripening stages, as previously reported for low-cost MBT units [37].

Table 2 also shows the distribution of the BP in the 8 potentially biodegradable categories of materials. The BMP distribution is not shown but was similar to the BP distribution. The overall BP and BMP of initial MSW were 267 ± 2 NL kg DM^{-1} and 136 ± 1 NL kg DM^{-1}, respectively (Table 3). These results are of the same order as data reported in the literature for untreated MSW: BP is about 210 L kg DM^{-1} for Leikam and Stegmann [38] in 400 days and for von Felde and Doedens [39] in 21 days, and about 320 L kg DM^{-1} for Francois et al. [14] in 1 or 2 months. The putrescible waste fraction was found to account for only 9% of the overall, which can be explained by its small mass proportion in the MSW (9%). Fine particles, papers, sanitary textiles and cardboards accounted for 26%, 20%, 17% and 16% of the overall BP, for a dry mass proportion of 21%, 13%, 8%, and 10%, respectively.

These results also showed that the initial MSW exhibited a very different distribution profile between BP and TOC$_{DM}$. For example, the fines contained 13% of the inlet MSW TOC$_{DM}$ but accounted for 26% of the BP. No direct correlation may therefore be made between the TOC$_{DM}$ and the BP and BMP distributions, since the nature and therefore the biodegradability of the organic matter was not the same in each category of materials.

3.1.2. DM and BP distributions in waste fractions at the outlet of sieve #1

At the outlet of rotary sieve #1, the coarse fraction CFS1 (>450 mm) was mainly composed of papers (13%), cardboards (24%), and plastics (24%) as shown in Table 2. This result indicated that the first sieving operation was not efficient in shredding large objects such as cardboard packages and large paper sheets. A significant amount of biodegradable organic matter (mostly

Table 3
Results of solid fractions analysis.

Fractions	Input (residual MSW)		CFS1 (reject)		IFS1		BFS2 (bales)	
	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
DM (%WM)	63.3	1.5	75.5	4.6	64.2	2.0	66.0	2.1
VS (%DM)	68.6	1.1	79.5	1.0	75.7	3.2	79.7	3.5
OOM (%DM)	43.1	0.0	37.7	2.0	43.4	1.0	36.0	0.1
TOC_{DM} (%DM)	35.2	2.0	41.6	2.7	39.2	2.4	41.9	3.4
BP_{90} (NL kg DM^{-1})[a]	267.4	1.4	280.8	16.2	268.2	4.8	231.9	21.0
BMP_{90} (NL kg DM^{-1})[a]	136.0	0.3	137.9	8.0	130.9	1.9	110.6	10.6
$\%CH_4$ (v/v)[b]	50.9	–	49.1	–	48.8	–	47.7	–

Fractions	FFS1		FFS2		$FFS1_{Stab}$		$FFS2_{Stab}$		$FFS1_{Mat}$		$FFS2_{Mat}$	
	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
DM (%WM)	56.8	6.2	41.6	2.4	54.5	0.5	47.5	1.1	60.4	11.2	44.3	2.0
Water field capacity (%WM)	57	–	61	–	55	–	60	–	48	–	53	–
VS (%DM)	50.9	1.6	76.2	0.1	43.4	0.6	65.1	3.5	38.9	3.9	57.8	1.5
OOM (%DM)	45.9	0.8	53.9	6.7	36.4	3.3	37.9	3.0	30.7	2.2	26.1	0.7
TOC_{DM} (%DM)	24.5	1.2	32.5	5.5	26.5	4.8	34.9	2.3	24.3	4.9	28.9	2.3
BP_{90} (NL kg DM^{-1})	215.0	42.8	290.8	33.3	50.6	9.8	231.5	22.6	27.7	14.4	63.7	19.4
BMP_{90} (NL kg DM^{-1})	113.9	29.8	134.7	20.6	22.7	2.8	104.9	6.0	16.7	7.9	34.6	7.4
$\%CH_4$ (v/v)[b]	53.0	–	46.3	–	44.8	–	45.3	–	60.3	–	54.3	–
RI_4 (g O_2 kg DM^{-1})	81.4	4.6	98.5	12.2	40.2	7.5	53.9	18.1	11.6	3.4	17.7	0.5
SHC_{10} ($\Delta T_{max} = T_{max} - T_{amb}$)	50.3	3.3	48.0	0.2	27.2	8.8	37.1	2.5	17.0	3.0	16.3	3.8
Maturity grade[c]	I		I		III		II		IV		IV	

Ave.: average result; SD: standard deviation; WM: wet matter; DM: dry matter; VS: volatile solids; OOM: oxidative organic matter; TOC_{DM}: total organic carbon; BP: biogas potential; BMP: bio-methane potential; RI_4: respiration index; SHC_{10}: self-heating capacity; MSW: municipal solid waste; CFS1: coarse fraction from sieve #1; IFS1: intermediate fraction from sieve #1; BFS2: baled fraction from sieve #2; FFS1: fine fraction from sieve #1; FFS2: fine fraction from sieve #2. Stab: after the stabilization step; Mat: after the maturation step.

[a] BP and BMP estimated from BP and BMP of each waste category and taking into account their dry matter ratio in the considered fraction [31].

[b] Mean CH_4 content in the biogas produced during BP test.

[c] Maturity grade ranges from I (fresh material) to V (compost completely mature).

papers and cardboards) with high VS, OOM and TOC_{DM} contents (Table 3) was therefore landfilled in cell #3, without any biological pretreatment. Consequently, the BP and BMP of the waste landfilled in cell #3 (CFS1) were as high as 281 ± 17 NL kg DM^{-1} and 138 ± 8 NL kg DM^{-1}, respectively (Table 3). The fine fraction FFS1 (<70 mm) exhibited lower biogas and bio-methane potentials: 215 ± 43 NL kg DM^{-1} and 114 ± 30 NL kg DM^{-1}, respectively (Table 3). Fine elements (<20 mm) were logically predominant in that fraction (Table 2). It can be concluded from these results that sieving operations must be combined with biological treatment when dealing with MSW in a MBT.

3.1.3. DM and BP distributions in waste fractions at the outlet of the ARB and sieve #2

Table 2 shows that the contents in cardboards and papers were almost the same in the 50–450 mm BFS2 fraction obtained after ARB and sieve #2 (Table 2) as in the 70–450 mm IFS1 fraction (30%) at the inlet of the ARB (Table 2). Moreover, the VS, OOM, and TOC_{DM} contents as well as BP and BMP were quite similar in these two fractions (Table 3). These results underlined the incomplete efficiency of the ARB in shredding the papers and cardboards. The residence time of 2 days in the ARB was therefore shown to be too short to allow a particle size reduction down to 50 mm through biodegradation and mechanical shredding of middle-size organic materials. Indeed, it is illusive to believe that 2 days is enough for a waste stabilization. Consequently, a large amount of potentially biodegradable organic matter was baled and landfilled in cell #2 (BFS2 fraction) as shown by the high biogas potential of 232 ± 21 NL kg DM^{-1} and the high VS, OOM and TOC_{DM} contents of 79.7%, 36.0%, and 41.9%, respectively (Table 3).

As already observed on FFS1 fraction (<70 mm), fine elements were also found to be logically predominant in FFS2 fraction (<50 mm) (Table 2). Fraction FFS2 was characterized by VS (76.2%), OOM (53.9%) and TOC_{DM} (32.5%) contents, which were higher than in FFS1 fraction, as shown in Table 3. Moreover, the BP and BMP (291 ± 34 NL kg DM^{-1} and 135 ± 21 NL kg DM^{-1}, respectively) were also higher than in FFS1 fraction, thereby confirming the poor biodegradation efficiency of the ARB due to the short residence time. These data were also confirmed by the higher content of inert materials in FFS1, with 10.5% of glass and 6.0% of unclassified inert materials, as compared to FFS2 (respectively 3.2% of and 0.9%).

3.1.4. Biological stability

Biological stability indices (BP_{90}, $BMP_{90,}$ RI_4 and SHC_{10}) of fine fractions FFS1 and FFS2 are shown in Table 3. The fresh fine fractions FFS1 and FFS2 were characterized by an average BP_{90} of 215 and 291 NL kg DM^{-1}, respectively.

After the 6-week forced-aeration step, BP_{90} dropped to 51 ± 10 NL kg DM^{-1} in $FFS1_{Stab}$ but remained high (232 ± 23 NL kg DM^{-1}) in $FFS2_{Stab}$. The lower biological stability of $FFS2_{Stab}$ as compared to $FFS1_{Stab}$ was confirmed by the results obtained for RI_4 and SHC_{10}. These results indicated that the forced-aeration stage was efficient to reduce the BP of FFS1 fraction (76% reduction of BP_{90}) but not that of FFS2 fraction (only 20% reduction). This observation was partly explained by the nature of the organic matter in each fraction. Indeed, FFS1 is the fine fraction (<70 mm) generated from the first sieving operation of input MSW and thereby contains a larger proportion of putrescible waste (11.0% in FFS1 vs. 2.6% in FFS2, Table 2). FFS2 is the fine fraction (<50 mm) obtained from the treatment of IFS1 through the ARB and the sieve #2 (Fig. 1), and therefore contains more recalcitrant organic compounds such as hemicellulose–cellulose and ligno-cellulose complexes, as illustrated by the higher content in papers and cardboards (8.8% in FFS2 vs. 2.4% in FFS1, Table 2). Moreover, bulk density, porosity, particle size, nutrient content, C/N ratio, temperature, pH, moisture and oxygen supply have demonstrated to be key for composting optimization [40,41]. Probably, these parameters were not optimized (too high moisture content or lack of porosity for instance). Although porosity was not

Table 4
Overall mass balance expressed in dry matter (DM), volatile solids (VS), total organic carbon (TOC_{DM}), oxidative organic matter (OOM), biogas potential (BP), and bio-methane potential (BMP).

Fractions	MSW (input)	CFS1 (reject)	IFS1	FFS1	$FFS1_{Stab}$	$FFS1_{Mat}$	Metals	BFS2 (bales)	FFS2	$FFS2_{Stab}$	$FFS2_{Mat}$	Ave. loss (%)	SD
DM balance	100.0	14.9	54.9	30.2	22.9	20.0	2.7	32.6	13.8	12.3	11.0	18.9	0.1
VS balance	100.0	17.2	60.4	22.5	14.5	11.4	0.0	37.8	15.3	11.6	9.3	24.3	0.4
TOC_{DM} balance	100.0	17.6	61.3	21.1	14.2	11.1	0.0	38.9	12.7	11.4	9.1	23.3	1.1
OOM balance	100.0	12.9	55.0	32.1	19.2	14.3	0.0	27.2	17.4	10.9	6.6	39.0	1.1
BP balance	100.0	17.4	61.0	21.6	4.9	2.3	0.0	31.3	16.7	11.7	2.8	46.2	5.7
BMP balance	100.0	17.6	61.0	21.4	4.5	2.8	0.0	30.7	15.9	10.9	3.2	45.6	7.2

MSW: municipal solid waste; CFS1: coarse fraction from sieve #1; IFS1: intermediate fraction from sieve #1; FFS1: fine fraction from sieve #1; BFS2: baled fraction from sieve #2; FFS2: fine fraction from sieve #2. Ave.: average; SD: standard deviation; Stab: after the stabilization step; Mat: after the maturation step.

measured, air filled porosity can be measured using air pycnometry as suggested by Ruggieri et al. [42]. Results obtained for $FFS1_{Stab}$ are a little higher than those obtained in a MBT plant treating non-selected MSW after 9 weeks (3 weeks more than for $FFS1_{Stab}$) of forced aeration by Barrena et al. [11]: RI_4 was 31.7 g O_2 kg DM^{-1} (40.2 g O_2 kg DM^{-1} for $FFS1_{Stab}$), and TOC_{DM} was 19.7% (26.5% DM for $FFS1_{Stab}$). Moreover, results obtained for $FFS1_{Stab}$ are in agreement with the values obtained for source-separated organic fraction of municipal solid waste [40].

After the 15-week ripening step, the BP strongly dropped in $FFS1_{Mat}$ and $FFS2_{Mat}$ with BP_{90} average values of 28 and 64 NL kg DM^{-1}, respectively. The results obtained from the SHC_{10} and RI_4 tests showed similar trends. It was therefore shown that the ripening stage was efficient in biodegrading the organic matter in $FFS2_{Stab}$ (72% reduction of BP_{90} between $FFS2_{Stab}$ and $FFS2_{Mat}$). It can be suggested that the forced aeration of FFS2, although not efficient to sufficiently stabilize $FFS2_{Stab}$, induced a partial degradation of the organic matter, which made it progressively biodegradable over the 15 weeks of ripening. On the other hand, since $FFS1_{Stab}$ was well stabilized by the forced-aeration treatment, the ripening stage was relatively less efficient (45% reduction of BP_{90}). At the outlet of the treatment line, $FFS1_{Mat}$ was shown to be more biostable than $FFS2_{Mat}$. In both fractions, however, the RI_4 values (11.6 ± 3.4 and 17.7 ± 0.5 mg O_2 g DM^{-1}, respectively for $FFS1_{Mat}$ and $FFS2_{Mat}$) were higher than the regulatory limit considered in Germany and Austria (5 and 7 mgO_2 g DM^{-1}, respectively).

Methane percentage (Table 3) was approximately 50% (v/v) in coarse fractions. It increases to 60% in $FFS1_{Mat}$ and 54% in $FFS2_{Mat}$. In fresh fractions, the high quantity of sugars leads to a high carbon dioxide yield and consequently a lower methane percentage. On the contrary, maturated fractions have a lower carbon dioxide yield and a higher methane percentage. In MSW landfills, methane percentage (v/v) is in the range 37–62% [43].

3.2. *Mass balance on DM*

Results of mass balance on the industrial plant are given in Table 4, Figs. 1 and 2. Globally, the average results from the two campaigns were similar to the results from the first campaign previously published [18], as shown by standard deviation (Fig. 1). The overall mass balance for a 100 kg (DM) input of MSW into the MBT unit showed that a mass of 78.4 kg DM was landfilled into the three cells, and 2.7 kg of ferrous metals were recovered. The treatment unit therefore reduced the mass of landfilled waste by 21.6% as compared to direct landfilling of all input MSW. Biodegradation over the treatment line reduced the dry mass by 18.9% with 5.8% reduction over the 2-day ARB treatment, 8.8% during the 6-week forced-aeration stage, and 4.3% during the 15-week ripening stage. 14.9% of the input MSW were landfilled in cell #3 without any biological pretreatment (fraction CFS1 made of coarse materials >450 mm), 32.6% were baled (fraction BFS2) and landfilled in cell #2, and 31.0% were landfilled in cell #1 as residual waste ($FFS1_{Mat}$ and $FFS2_{Mat}$ fractions).

3.3. *Mass balance on VS and TOC_{DM}*

Table 4 and Fig. 2 show that for an input mass of 100 kg of organic matter (VS) treated in the unit, 20.7% was landfilled in cell #1 ($FFS1_{Mat}$ and $FFS2_{Mat}$ fractions), 37.8% in cell #2 (baled fraction BFS2) and 17.2% in cell #3 (CFS1 fraction). The overall treatment therefore reduced the mass of landfilled organic matter (VS) by 24.3% as compared to a situation where all input MSW would have been landfilled directly without any treatment. The 2-day ARB treatment was responsible for 7.3% reduction of VS, the 6-week forced-aeration accounted for 11.7%, and the ripening stage for 5.4% (Table 4).

Similar results were obtained with the organic carbon balance with an average loss of 23.3 ± 1.1%, thereby confirming the good correlation between VS and TOC_{DM} contents. These two parameters (VS and TOC_{DM}) do not differentiate organic matter (carbon from natural (potentially biodegradable) or synthetic origins) and cannot be used as stability indices. However, they can be used to estimate carbon emission over the treatment line. In the present case, carbon emissions were calculated from TOC_{DM} loss to around 82 g of C for 1 kg DM of input MSW. Indeed, 1 kg DM of input waste contains 352 g of organic C (Table 3). The TOC_{DM} loss is 23.3%, that is to say 82 g. Considering in a first approach that all C was emitted as CO_2, the overall CO_2 emission was estimated at 300 g of CO_2/kg DM (or 190 g of CO_2/kg WM) of input MSW. This value is comparable to the one obtained by Amlinger et al. [44] who estimated CO_2 produced in a MBT in the range 120–185 g of CO_2/kg WM. Carbon (respectively CO_2) emissions from the ARB step, the forced-aeration step, and the ripening step were, respectively, estimated at 34 g (respectively 125 g), 29 g (respectively 106 g) and 19 g (respectively 70 g). CO_2 produced this way is not fossil derived, and therefore, it is not counted as a green house gas emission [44]. To determine environmental impact due to gaseous emissions associated to biological steps, one can use the methodology proposed by Cadena et al. [45].

3.4. *Mass balance on OOM, BP and BMP*

Following the same approach as above, the overall reduction of OOM (corresponding to potentially degradable organic matter) in the treatment unit was calculated to be 39.0 ± 1.1% (Table 4 and Fig. 2). This value was lower than the 55–60% degradation of biodegradable organic matter suggested by Fricke et al. [7] for the German regulation as the objective of stabilization in MBT plants. The 2-day ARB treatment accounted for 10.4% reduction of OOM, the 6-week forced aeration for 19.4%, and the ripening stage for 9.2% (Table 4). As much as 61% of the input OOM was therefore landfilled. Most of it (27.2% of input OOM) ended up in cell #2 (bales); the rest was landfilled in cell #1 (20.9%) as stabilized waste and in cell #3 (12.9% as coarse fraction CFS1).

The overall reduction of BP and BMP was estimated at 46.2 ± 5.7% and 45.6 ± 7.2%, respectively (Table 4). The MBT plant therefore achieved a reasonable stabilization of the MSW, which was its first objective. BP reduction was attributed for 13.0%, 21.7%

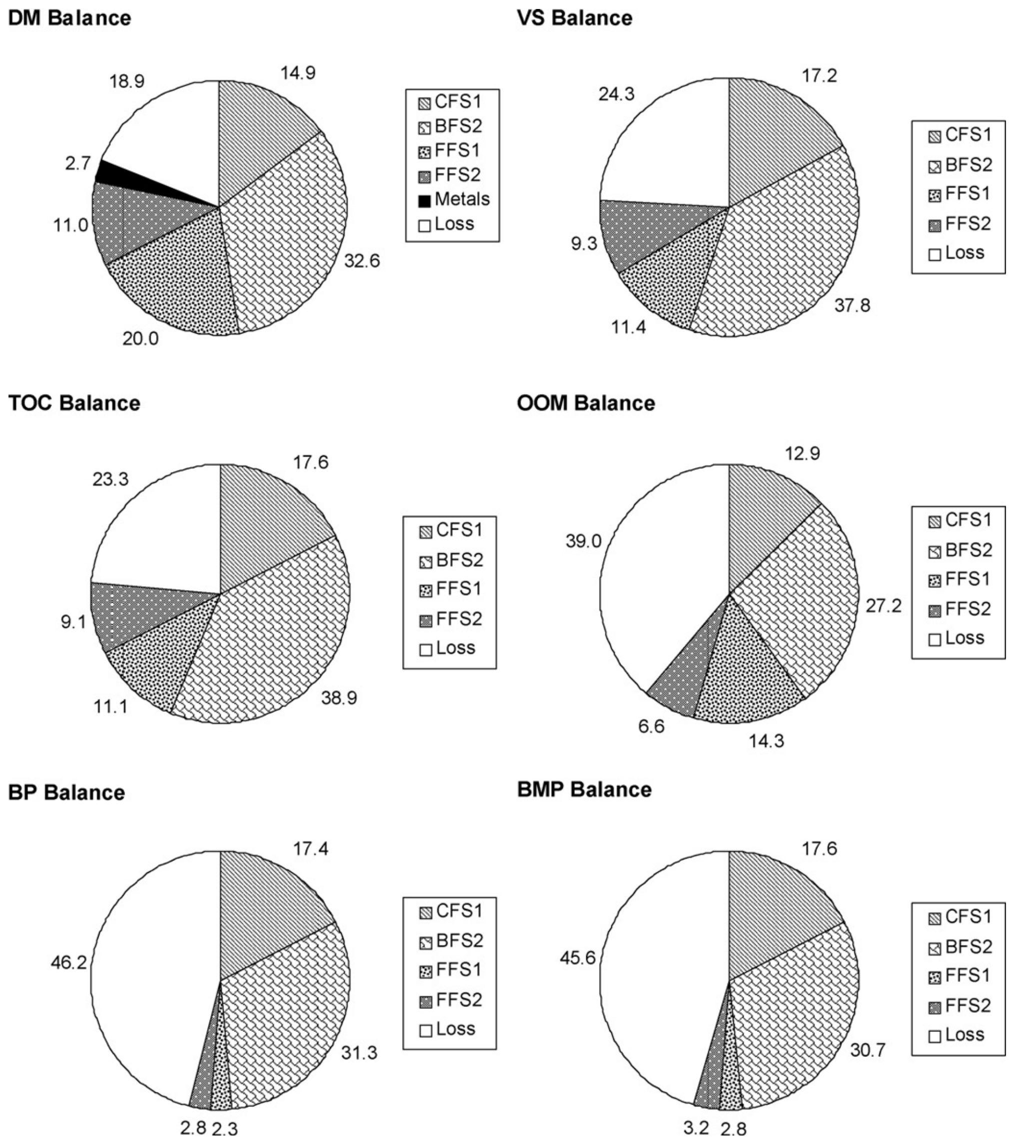

Fig. 2. Overall mass balance of the treatment expressed in dry matter (DM), volatile solids (VS), total organic carbon (TOC_{DM}), oxidative organic matter (OOM), biogas potential (BP), and bio-methane potential (BMP).

and 11.5% to the ARB step, the forced-aeration stage, and the ripening stage, respectively. Most of the residual BP was concentrated in fraction BFS2 which was baled and landfilled in cell #2 (31.3% of the initial biogas potential of 267.4 NL kg DM^{-1} represented by the input MSW). The rest (17.4% and 5.1%, respectively) was landfilled in cell #3 (coarse fraction CFS1) and cell #1 (stabilized waste).

OOM, BP and BMP parameters revealed very similar trends, indicating that these parameters were fairly well correlated and may be considered as good indicators of the level of biostability of the waste. Indeed, using principal component analysis, Achour [46] showed that the relevance of OOM and BP_{90} to characterize waste stability were equivalent.

4. Overall discussion

4.1. Efficiency of sieve #1

Sieve #1 was designed to sort out the coarse fraction CFS1 considered as poorly biodegradable. This fraction was found however to still contain 12.9% of the OOM received on the plant in the input MSW and 17.4% of the initial BP, which were landfilled in cell #3 without any pretreatment (Fig. 2, Table 4). Table 2 shows that 73% of the residual BP in CFS1 fraction was due to papers, cardboards and textiles, which were therefore shown to be the three major categories of materials potentially responsible for biogas emissions from landfill cell #3 over the medium and long term. The low initial moisture content of the waste materials in CFS1 fraction (24.5 ± 4.6%, Table 3) will probably induce a low biological activity in cell #3. However, a potential risk of biogas emissions does exist.

4.2. Efficiency of ARB and sieve #2

Considering the inlet (IFS1) and the outlet (BFS2 and FFS2) of the ARB and sieve #2, OOM and BP reductions were calculated to be 19.5% and 21.4% (based on the OOM and BP at the inlet of the ARB), using the data given in Table 3 and Table 4. The ARB therefore achieved a reasonable degradation of organic matter. However, the efficiency of sieve #2 to concentrate biodegradable organic matter into FFS2 (<50 mm) and sort it out of BFS2 (>50 mm) remained insufficient. Indeed, Fig. 2 shows that 27.2% of OOM and 31.3% of BP from the input MSW were finally baled and landfilled in cell #2, corresponding respectively to 49.3% and 51.3% of OOM and BP entering the ARB. This is confirmed by Table 2 which shows that BFS2 after metal separation had relatively high concentrations of biodegradable organic matter with 4% of putrescible waste, 23% of papers, 6% of cardboards, 5% of textiles and 9% of sanitary textiles. Table 2 also shows that the residual BP in BFS2 was mainly due to the presence of papers, textiles and sanitary textiles (71% of the global BP). Cardboards (11%) and composites (11%) also showed a significant contribution to the residual BP of the baled fraction. Despite relatively satisfactory biodegradation efficiency, the ARB was not efficient in shredding the coarse organic materials. The short residence time of only 2 days might explain in part this observation. Another reason might be the relatively high humidity of the waste, due the addition of leachate into the ARB with the objective to reach favorable moisture conditions. Initially at 35.8 ± 2.0% in IFS1 (inlet of ARB), the moisture content was still high after 2 days of aerobic treatment, with 34.0 ± 2.1% and 58.4 ± 2.4% for BFS2 and FFS2, respectively (Table 3), although the temperature reached 65 °C in the ARB. The relatively high moisture content of the waste at the output of the ARB probably had a negative effect on the efficiency of sieve #2.

4.3. *Efficiency of forced aeration and ripening stages*

The main purpose of the forced aeration and ripening stages in the MBT plant of Mende was the degradation of the biodegradable organic matter, and the biological stabilization of the fine fractions prior to landfilling. These two objectives were evaluated by considering on the one hand the OOM and BP balance (Table 4) and, on the second hand, the stability indices RI_4, SHC_{10} and BP_{90}, of the maturated fractions $FFS1_{Mat}$ and $FFS2_{Mat}$ (Table 3).

As mentioned above (Section 3.4), a strong decrease of OOM and BP was observed during the biological treatments of the fine fractions FFS1 and FFS2. Using the data given in Tables 3 and 4, it was calculated that the forced aeration and ripening stages altogether degraded 57.7% of the OOM (based on the mass of OOM at the inlet of the forced-aeration process), with 39.0% over the 6 weeks of the forced aeration and 18.7% over the 15 weeks of ripening. Using the same approach, it was also calculated that the BP dropped by 88.1% between the input of the forced-aeration stage and the output of the ripening stage, with 61.9% decrease at the level of the forced-aeration stage, and 26.2% at the ripening stage. These observations showed the relatively good efficiency of the biological treatments to decrease the load of biodegradable organic matter to be ultimately landfilled. The stabilization step aims at biodegrading organic matter and leads to high mass reduction, whereas the objective of the ripening stage is to biotransform organic matter into more chemically and biologically stable molecules (low mass reduction). In the present case, the ripening stage was found to play a significant role also in the biodegradation (roughly 20–25% of the total OOM reduction occurred during the ripening stage), and not only in the stabilization of the biodegradable organic matter. This observation suggests that the forced-aeration stage was not fully efficient. The two parameters OOM and BP provided similar qualitative information, but the decrease of BP was found to be proportionally higher than that of OOM, indicating that the two parameters are not directly correlated.

The stability indices BP_{90}, SHC_{10} and RI_4 in the stabilized and maturated fractions (Table 3) were found to be higher than the limits usually considered for maturated organic matter in the literature [39], particularly for FFS2 fraction. The forced aeration of FFS2 fraction was particularly poorly efficient to biodegrade the organic materials as shown by the high BP_{90}, SHC_{10} and RI_4 in $FFS2_{Stab}$. This observation suggested that the conditions of aeration were not optimized for FFS2, due to its low particle size (<50 mm), the high proportion of fines below 20 mm (68.3%, Table 2) and its high content of degradable organic matter OOM (Table 3). Operational design, especially aeration procedure, should therefore be optimized for FFS2 with a higher frequency of air blowing and aspiration, and with a higher frequency of waste mixing.

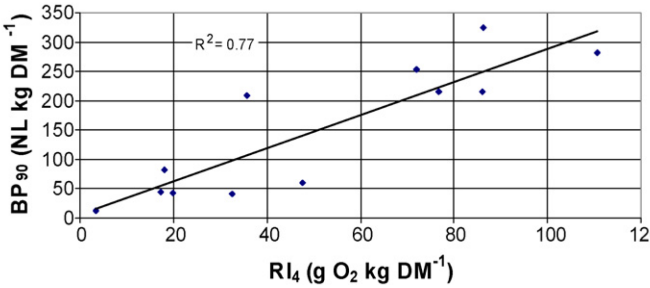

Fig. 3. Correlation between respiration index (RI_4) and biogas potential (BP_{90}) measured on samples FFS1, FFS2, $FFS1_{Stab}$, $FFS2_{Stab}$, $FFS1_{Mat}$ and $FFS2_{Mat}$ from both campaigns.

4.4. *Discussion about biological stability indices*

BP_{90} is a good indicator of anaerobic degradation since, in these conditions (90 days), the total biogas production is expressed. Moreover, due to anaerobic conditions, BP is representative of possible gas generation in landfills. But it cannot be used as a routine test because of the long duration if the test [13]. For that reason, it is important to find some correlations between BP_{90} and other tests that would be easier to implement. Several authors found a linear correlation between BP and respiration index [4,9–11]. Indeed, considering the results from both campaigns obtained on fine fractions (before and after stabilization and maturation steps), a correlation between RI_4 and BP_{90} could be found (Fig. 3). The R^2 value is 0.77, and is better than R^2 value obtained by Cossu and Raga [9] on a pretreated waste between GB_{21} and RI_4 (0.60). Other correlations could be found between gas generation and TOC in the eluate [4], between characteristics of leachates and respiration index [9], between respiration index and black index [9], between dynamic and static respiration index [11]. When the overall efficiency of a waste treatment plant has to be evaluated, respiration indices are strongly recommended [9,10,16], and indeed, in the case of the MBT plant of Mende, RI_4 was a reliable technique. Yet, according to Wagland et al. [13], no test method is currently sufficient for routine biodegradability assessment and further research is needed to develop a rapid and cost-effective test method.

5. Conclusion

Although the overall mass reduction was relatively limited (18.9% on a dry mass basis), the treatment unit was shown to achieve a reasonable stabilization of the organic matter before landfilling, as shown by the decrease of the OOM load (39.0% on the basis of dry OOM mass) and the BP (46.2% decrease). Some specific stages of the treatment line were shown to need process optimization: indeed, several results could be improved such as the efficiency of the aerobic rotating bioreactor to reduce the particle size of the waste, the efficiency of sieve #2 to segregate organic materials, and the efficiency of the forced-aeration stage to biodegrade FFS2 fraction. Recommendations to improve the MBT process include: combining sieving operations with biological treatment, increasing residence time in the ARB, improving aeration procedure and turnings during the stabilization step, especially for FFS2 (moisture and porosity control is also suggested).

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