VNiVERSiDAD D SALAMANCA

CAMPUS OF INTERNATIONAL EXCELLENCE

DEPARTMENT OF CHEMICAL ENGINEERING

UNIVERSITY OF SALAMANCA

Summary of PhD THESIS

OPTIMIZATION IN THE TREATMENT OF ORGANIC AND REJECT FRACTIONS FROM MUNICIPAL SOLID WASTE

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With the aim of promoting a correct management of municipal solid waste (MSW), the European Union drafted the European Directive 1999/31/EC, one of the most ambitious and important European policies on waste. This regulation establishes the hierarchy to be followed by waste management, in this order, reduction, reuse, recycling, recovery and landfill and additionally, reduction targets of biodegradable material sent to landfill were set for UE countries. In order to reach these goals, in the region of Castilla y Leon (Spain) during the last decade, the number of bins for selective collection was increased and up to twelve mechanical-biological treatment plants (MBTPs) were built. In these MBTPs, after recyclable fractions like plastics, metals or paper are recovered, the organic matter present in MSW is stabilized by biological treatments. Biogas and/or compost are produced in these biological stages and consequently, the amount of biodegradable material landfilled is reduced.

However, years after the enactment of the European Directive, the information regarding waste management in the studied area is insufficient. Important information such as MSW composition and its evolution over the time or the yields achieved by the MBTPs in this region are still unknown. A deeper knowledge about these aspects might boost the development and optimization of processes which could be real alternatives for MSW management. Currently, one of the main challenges of Chemical Engineering is the transformation of waste into valuable raw materials for other processes. Moreover, due to the large amount of MSW generated annually worldwide, any progress in this field causes a huge impact. Since the organic fraction and the reject or refuse derived fuel (RDF) are the main streams generated by the current management model, this work will be focus on the optimization of the treatment of both fractions.

The organic matter can be stabilized by one of both biological treatments in this region, composting or anaerobic digestion. The final product of composting systems is a bio-stabilized material that, if shows enough quality, can be used as organic amendment or agricultural substrate. A bio-stabilized material is obtained also as final product in the anaerobic digestion after biogas production while biogas is used to generate electricity. A complete analysis of both biotechnologies will reveal the current performance of both processes as well as identify their strengths and weaknesses so that, alternatives for technological and environmental optimization can be proposed. On the other hand, results obtained after characterizing the reject fraction from MBTPs, will allow assessing the compliance degree with the European Directive. In addition, other valorisation options can be evaluated as alternative management to landfilling according to the waste hierarchy hence, the study should include a Life Cycle Analysis (LCA) of the current management system in Castilla y León and the proposed alternatives.

At the beginning of this investigation, several technical visits to the 10 MBTPs in operation at that time were conducted. The objective was to gather the most relevant information about the unit operations included in the design of the MBT plants and the equipment specifications, paying particular attention to composting and anaerobic digestion. In general terms, all the plants showed similar configuration with a first separation of the organic matter as the undersized fraction of 80-90mm trommel, and a subsequent recovery of recyclable materials carried out manually in 9 of the 10 MBTPs. Figure 1 shows a diagram of the typical operation of the MBT plants in this region.

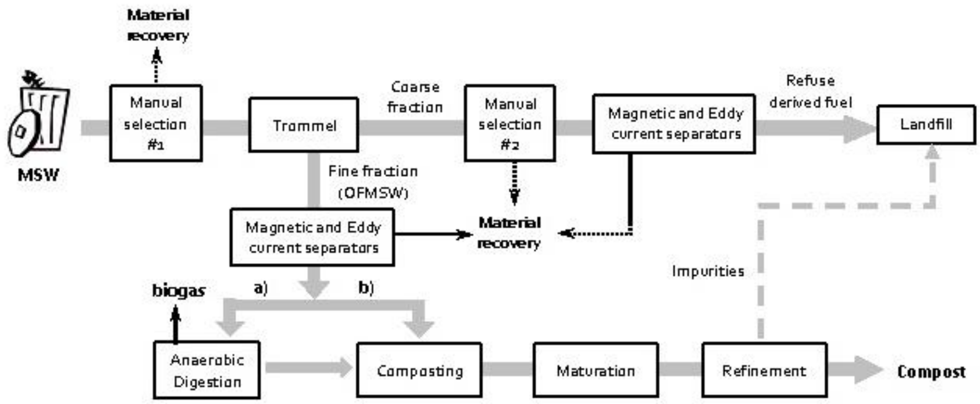

Figure 1. Typical operating diagram of the studied MBT plants

In 5 of the MBTPs the organic matter can be treated by anaerobic digestion although in 3 of them this module was stopped. Managers alleged an excessive content of inert material in the input as the main cause of the stoppages. On the other hand, in all the MBTPs the composting modules were working. There are composting tunnels in all the MBTPs where the organic matter or the digestate obtained after anaerobic digestion are stabilized. Therefore, a biostabilized material is produced in all the MBTPs which can be sold as organic amendment although with very different acceptance depending on the local market. Another problem detected at this stage is the early overload of the landfills adjacent to each MBTP. According to the provided data, as average, 70% of the MSW input is landfilled as reject of the MBTPs. Table 1 summarizes the technical features of the studied MBT plants.

In order to know the MBTP yields in the studied region, several characterizations were performed to the main streams: MSW (MBTP input), reject or RDF (currently landfilled), organic matter (biological processes input) and composted organic matter (composting process output). After 32 characterizations, the average composition was obtained for both MSW and RDF. MSW composition was updated for the first time in a decade while it is the first characterization of the RDF in this region (figure 2).

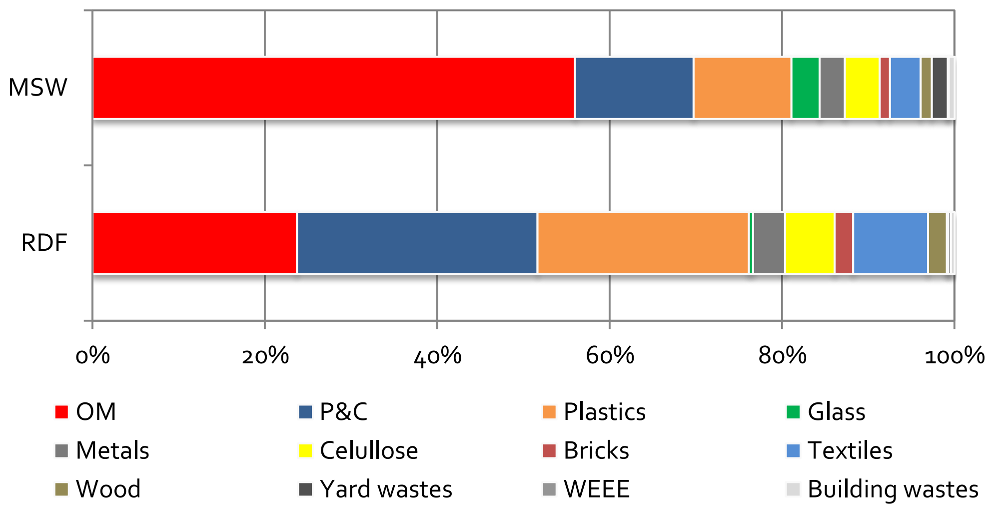

Figure 2. MSW and RDF average composition in Castilla y León.

Table 1. Technical features of composting processes in the studied MBT plants.

	Capacity (tons/year)	Type	Trommel		Feedstock to composting	Bulking agent	Tunnels		Maturation type and HRT (days)	Final refinement
			Length (m) x diameter (m)	Hole diameter			Number and (LxWxH in m)	HRT (days)		
MBTP 1	80000	I	12 x 2	90mm	Anaerobic digestate	Yogurt containers	6 (15x5x6)	15	windrows	Screen
MBTP 2	25400	II	12 x 2	80mm	OF <80mm	No	3 (25x5x4)	15	windrows	Gravity separator
MBTP 4	70000	II	12 x 3	90mm	OF <90mm	Yard trimmings	6 (30x4.5x5)	15-20	windrows	Trommel 10mm
MBTP 5	150000	I	12 x 1.5	300mm, 80 mm, 40mm	40mm<OF <80mm	No	20 (33x5x6)	15	tunnels (15 days)	Trommel 16 mm
MBTP 6	70000	I	15 x 2.5	80mm	Anaerobic digestate	Yard trimmings	8 (25x5x5)	15	windrows (>30 days)	Screen 15 mm
MBTP 7	60000	II	12 x 2	80mm	OF<80mm	No	6 (25x5x5)	15	windrows	Trommel 20 mm
MBTP 8	35000	II	12 x 2	80mm	OF<80mm	No	4 (20x4.7x5)	15	windrows (4-6 weeks)	Trommel 25 mm
MBTP 9	210000	I	12 x 2	80mm	OF<80mm	No	22	15	windrows	Gravity separator
MBTP 10	80000	II	12 x 2	80mm	OF<80mm	Yard trimmings	4 (20x5x6)	12-20	windrows	Trommel

The degree of compliance with European Directive 1999/31/CE and the Spanish transposition (RD 1481/2001) in the MBTPs of this region could be calculated based on the obtained RDF characterizations and mass balances provided by the MBTP managers. According to these results, objective of 2006 (25% of reduction on biodegradable waste landfilled in 1995) was fulfilled mainly because of the built of 10 MBTPs in those years. However, objective of 2009 (50% of reduction) was not reached, in spite of the important reduction achieved in the amount of RDF which is landfilled. The amount of biodegradable waste sent to landfill in 2009 is still 56.8% of the biodegradable waste landfilled in 1995. Additionally, in order to reach the objective of 2016 (65% of reduction) and taking into account the present trend, the amount of RDF currently landfilled should be reduced or increase the recovery of organic matter in the MBTP. Local objectives regarding to RDF and organic matter reduction in landfills, even more ambitious than those at European level, were not achieved either.

In relation to recyclable materials, more than 50% weight of the RDF is still composed of recyclable materials like paper and cardboard or plastic fractions. In general, mechanical systems showed higher recovery ratios than manual sorting systems. Up to 62% of ferrous and non-ferrous metals were recovered while manual recoveries like those for paper and cardboard reached 40% at best. These ratios could be increased by increasing the number of operators in the triage cabins or replacing them by innovative mechanical elements like the optical system installed in the MBTP 8 showing great efficiency. Manual recovery yields are clearly influenced by the price of recyclable materials, currently the highest rates are obtained for PET (polyethylene terephthalate) and beverage cartons with 60 and 40% respectively. Other plastics like HDPE (high density polyethylene) are also recovered in the manual triages in all the facilities. However, manual recovery of paper and cardboard is only carried out in 3 of 10 MBTPs, hence the high percentage of these material in RDF. This is one of the main reasons because of guidelines about biodegradable material in landfill are not met. Clearly, recovery rates of paper and cardboard should be increased in this region.

In order to evaluate other options for RDF treatment as alternative of landfilling and once the RDF composition is known, some of the most important energetic parameters such as moisture, elemental composition, high heating value (HHV) or ashes content were analysed (table 2). The moisture values (close to 20%) and the low heating value (LHV) of the RDF generated in the MBTP in Castilla y León (17 MJ/kg) indicate that the incineration of this fuel can be energetically profitable.

	MSW	RDF
HHV (MJ kg^{-1} of waste)	**10,16**	**18,28**
(MJ kg^{-1} of dry waste)	**18,97**	**23,44**
(MJ kg^{-1} of dry-ash free waste)	**26,52**	**26,95**
LHV (MJ kg^{-1} of waste)	**8,33**	**16,66**
(MJ kg^{-1} of dry waste)	**17,68**	**22,06**
(MJ kg^{-1} of dry-ash free waste)	**24,99**	**25,41**
Moisture (%)	**46,46**	**22,07**
Non-combustible material (% weight dry basis)	**15,23**	**10,10**
Specific weight (kg m^{-3})	**208,0**	**130,8**

Table 2. Properties of waste streams related to combustion.

Besides the RDF stream, performance of treatments applied to the organic matter has been evaluated. With this purpose, up to 30 characterizations were performed to inputs and outputs of both biological treatments anaerobic digestion and composting. Figure 3 shows the results of these characterizations. The organic fraction of municipal solid waste (OFMSW) is obtained as the undersized fraction from 80-90 mm trommel and results of its composition showed high percentage of inert material like plastics (9%) and glass (11%). Because of their inert nature, also appear in the output streams of composting systems and regardless of some of them can be used as structuring material (plastics case) must be removed in the refining step. Highly polluting elements like batteries must also be removed at this step since were found in 7 of the 30 characterized samples and should never appear in the biostabilized material. It seems clear that public awareness should be raise to segregate properly wastes and deposit this kind of hazardous waste in bins provided for such purpose. It would be necessary to analyse whether the number of containers is enough even in the smallest towns of this region and the environmental footprint of the global process with the particular population distribution of Castilla y León.

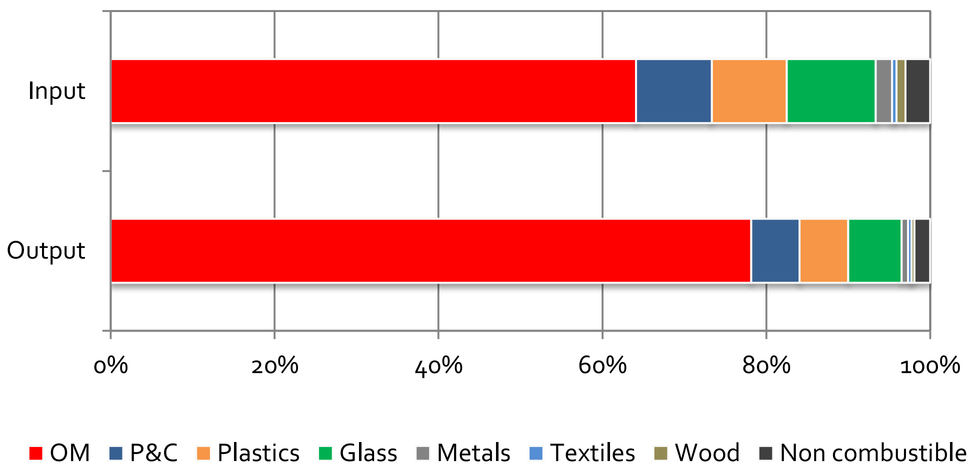

Figure 3. Average composition of input and output streams of composting processes.

With the aim of verify the quality of the main product of composting, the biostabilized, 3 samples of each of the 10 MBTPs were analysed. For this, the specific methodology recommended by fertilizer legislation was followed and results were compared with the limits established by RD 506/2013 concerning use of organic amendments as fertilizers and by RD 865/2010 for their use as agricultural substrates. Under this specific legislation, biostabilized samples should meet certain physical and chemical requirements in order to be considered fertilizers of class A, B or C depending on their quality (A is the best of them).

Results obtained for the biostabilized produced in this region -in parameters like moisture, organic matter percentage, C/N ratio, improper material content, particle size distribution, pH or nutrients and heavy metals concentration- were analysed (figures 4 to 13). Only 5 of the 10 MBTPs are producing a biostabilized in accordance with all the requirements of RD 865/2010 and can be used as agricultural substrates. Biostabilized from MBTPs 1, 2, 5, 8 and 10 showed organic matter percentage above 20% and heavy metals concentrations lower than Class B limits. Rest of the biostabilized have enough organic matter content but concentrations of Pb or Zn exceeding the limits of class B, which prevents its use in accordance with RD 865/2010.

As organic amendments, none of the biostabilized that fulfilled the requirements of RD 506/2013 get the best quality (class A), one of them can be considered as class B and the other two belong to class C so must meet certain dose limitations for its application to soils. Despite the presence of hazardous waste like batteries in the composting raw materials, concentration of heavy metals is not the main reason for the low quality showed by the biostabilized products. Only in the case of lead, two samples taken in MBTP 6 showed concentration levels higher than the allowed value (figure 9).

In addition, biostabilized from MBTP 6 shows the same problem as other five biostabilized products which cannot be used as organic amendment because of the high percentage of improper materials greater than 2 mm in size (from MBTPs 1, 5, 7, 8 and 9). It seems clear that, in general terms, the performance of the refining systems is worse than expected. In most MBTPs, the refining step includes trommels, densimetric tables and cyclones. The smaller mesh size in trommel, the less material is obtained but the lower impurities content also; similarly, some parameters of densimetric tables can be adjusted in order to improve the separation with certain loss of material. It would be desirable to increase the product quality by reducing the production to the accumulation of tons of poor quality product as currently happens. However, apparently the demand for this product is not related to quality; the highest quality biostabilized (MBTP 10) is given for free to local farmers while in other areas products with lower quality, even not meeting the legislation requirements, are highly appreciated. In order to guarantee the protection of soils in this region and also get a better acceptance of this product if the quality is good, biostabilized should be subjected to controls and quality certifications.

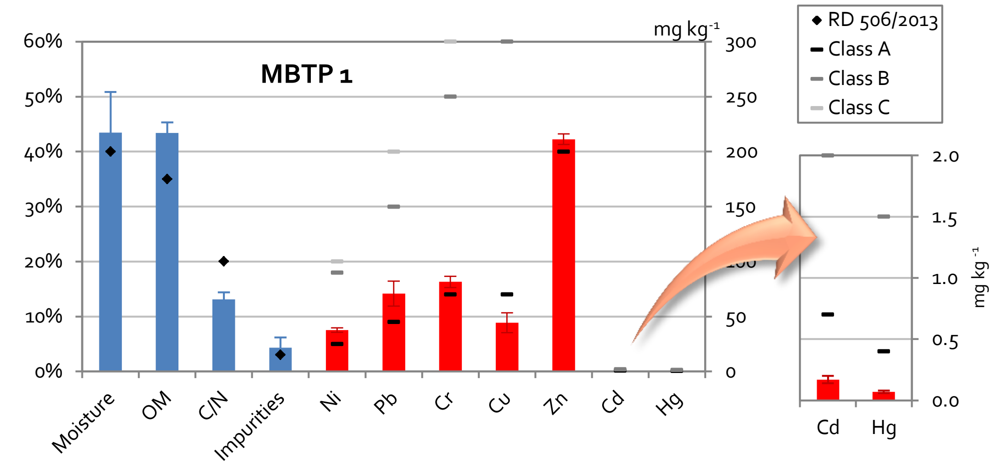

Figure 4. Biostabilized from MBTP 1

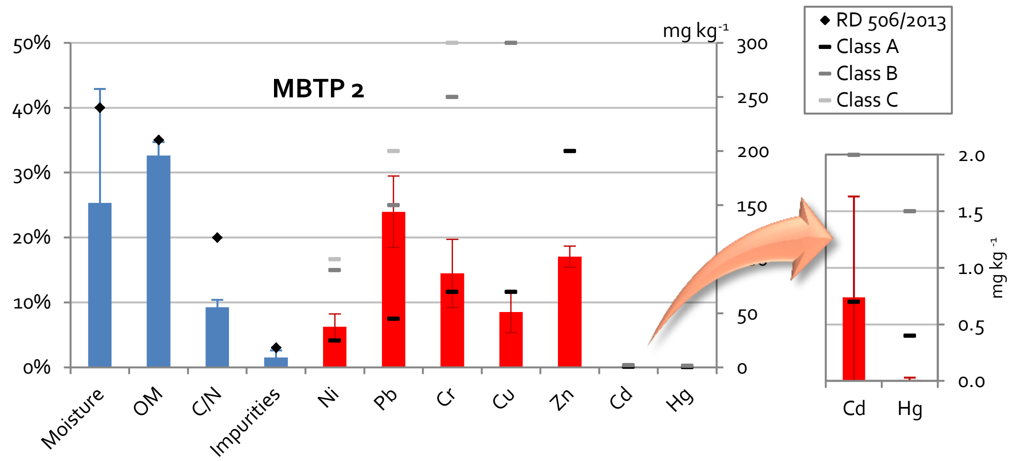

Figure 5. Biostabilized from MBTP 2

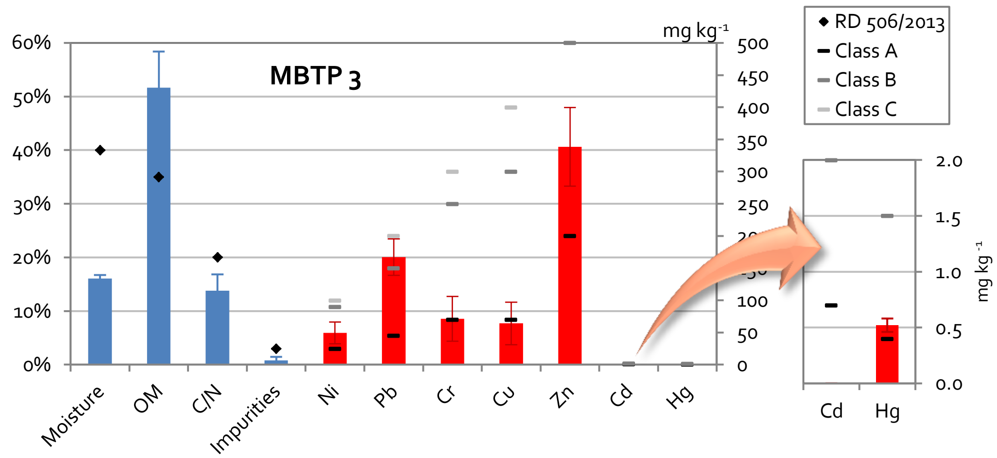

Figure 6. Biostabilized from MBTP 3

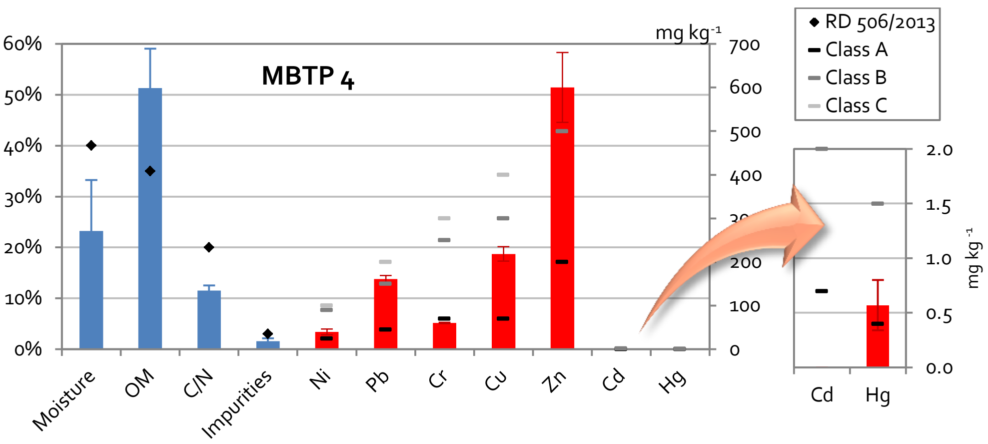

Figure 7. Biostabilized from MBTP 4

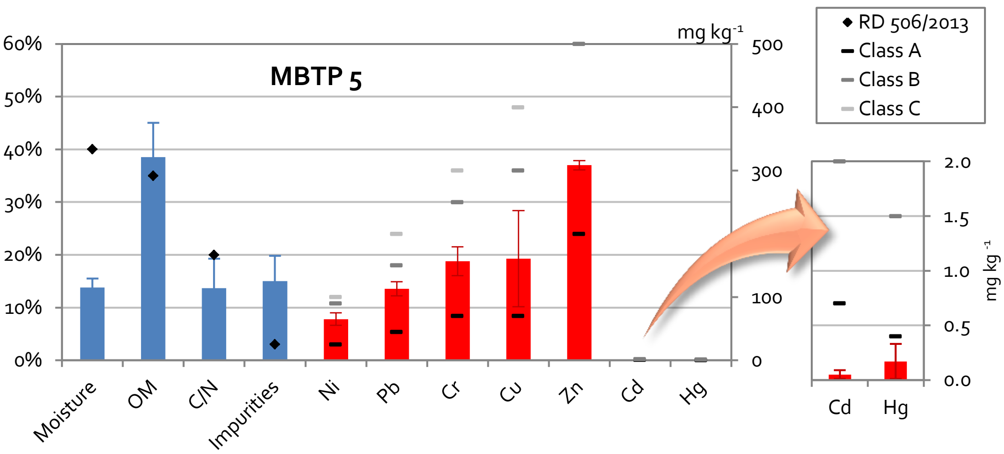

Figure 8. Biostabilized from MBTP 5

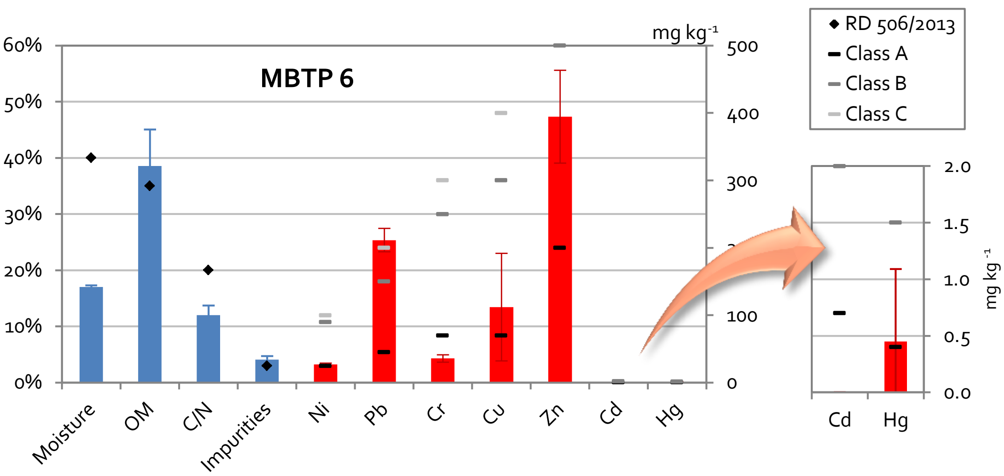

Figure 9. Biostabilized from MBTP 6

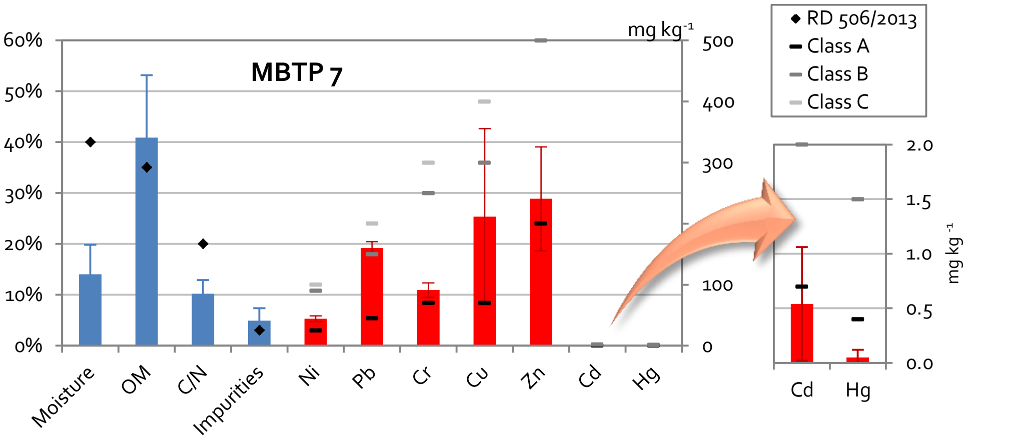

Figure 10. Biostabilized from MBTP 7

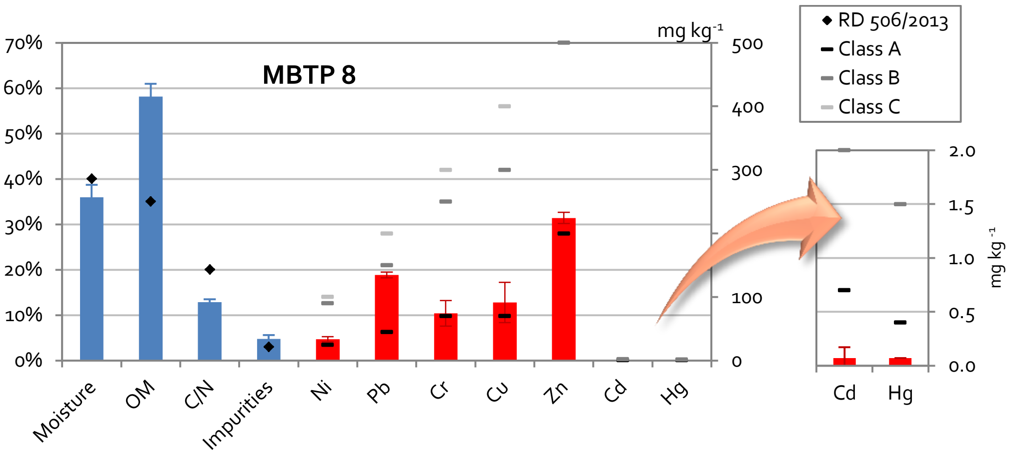

Figure 11. Biostabilized from MBTP 8

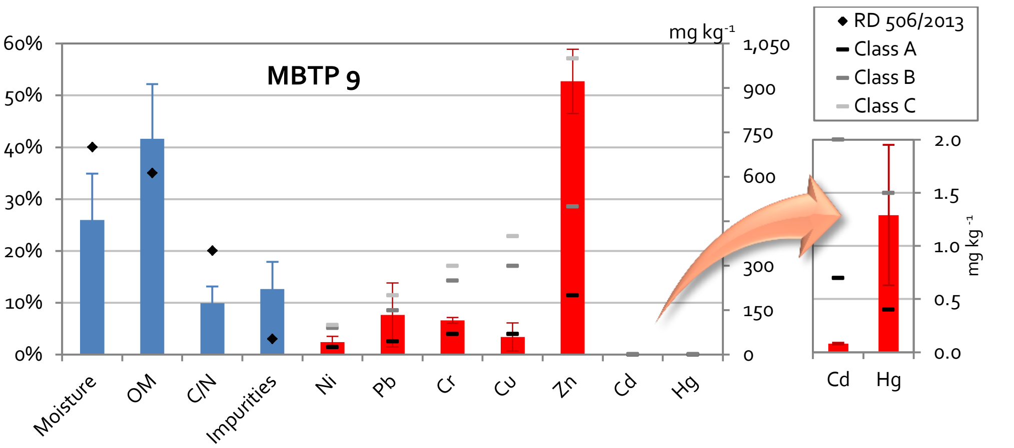

Figure 12. Biostabilized from MBTP 9

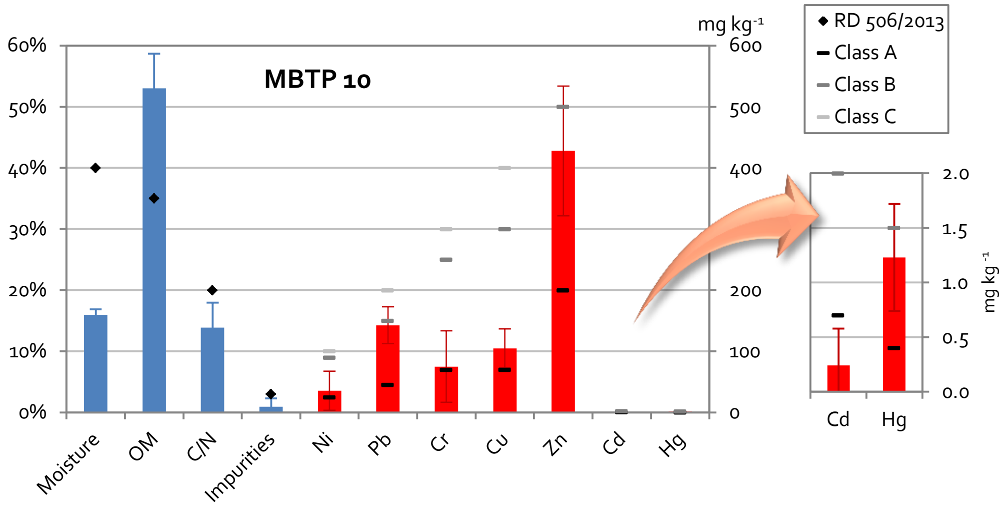

Figure 13. Biostabilized from MBTP 10

In the MBTPs the effluent from the anaerobic digester is centrifuged to separate the liquid phase (returned to the process) from solid phase (digestate). The digestate is sent to the composting tunnels and a complete composting cycle begins before selling it as organic amendment. Main legislation parameters were analyzed in the digestate to try to optimize this stage in those MBTP with biomethanization (figure 14). Results showed that the organic matter content, C/N ratio and rest of fertilizer requirements were adequate but the cadmium content was above the allowed limits. Since high concentration of heavy metals was not found in any of the samples of the biostabilized from MBTP 1, this fact should be considered as a single event although all this lot should be discarded. According to these results, moisture is the only parameter that should be adjusted after the anaerobic digestion so it could be possible to reduce the complete composting cycle to a single stage of maturation with the consequent saving in the operational cost. Nonetheless, it is necessary to increase temperature and aeration inside the tunnels to ensure a complete sanitation of the product.

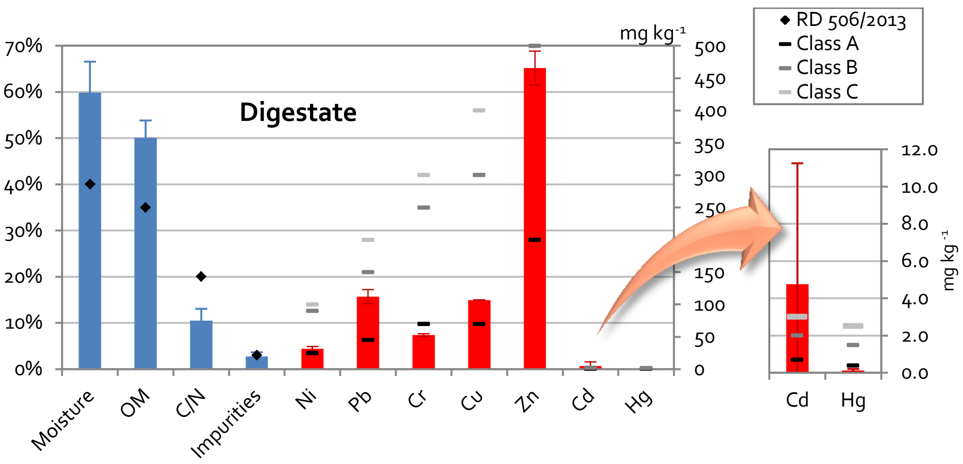

Figure 14. Digestate from MBTP 1

Furthermore, the operation of the anaerobic digestion technology installed in some MBTPs in this region does not show satisfactory results. In 2 of the 5 MBTPs with biomethanization module, it was stopped. One of them because of works for improving its performance, the organic matter reaches the reactor with high percentage of inert matter which should be removed before going into the digester. In the other case it is just an operation decision; the complete stream of OFMSW is treated by composting despite having the anaerobic digestion unit. MBTP 9 was the only that reported good results at this stage. Exceptionally, in this MBTP the anaerobic digestion is a dry process, i.e. total solid percentage inside the reactor is higher than the rest, and also the raw material is the organic fraction from a source selection (unique in the region). According to characterizations performed to OFMSW obtained as the undersized fraction of trommels, this stream showed a large amount of inert materials which should not be present in the source selected organic fraction. This process was studied in depth at laboratory scale; the OFMSW was treated by anaerobic digestion in a pilot plant under the conditions that are problematic for managers: wet way and not source selected raw material.

After an initial evaluation of the operation conditions, in which two discontinuous trials were carried out in parallel with source selected (figure 15) and not selected or mechanically sorted OFMSW (figure 16), an increased methane production was observed in the case of the source selected feedstock but the process is slower than in unselected one. The inoculum addition for source selected OFMSW can accelerate the process as shown in figures 15 and 16. This batch trial allowed us to confirm the feasibility of the process in the operating condition of MBTPs, i.e. not selected organic fraction, wet way, mesophilic regime and no inoculum addition and to select the hydraulic residence time (HRT) to maximize the biogas production, 20 days.

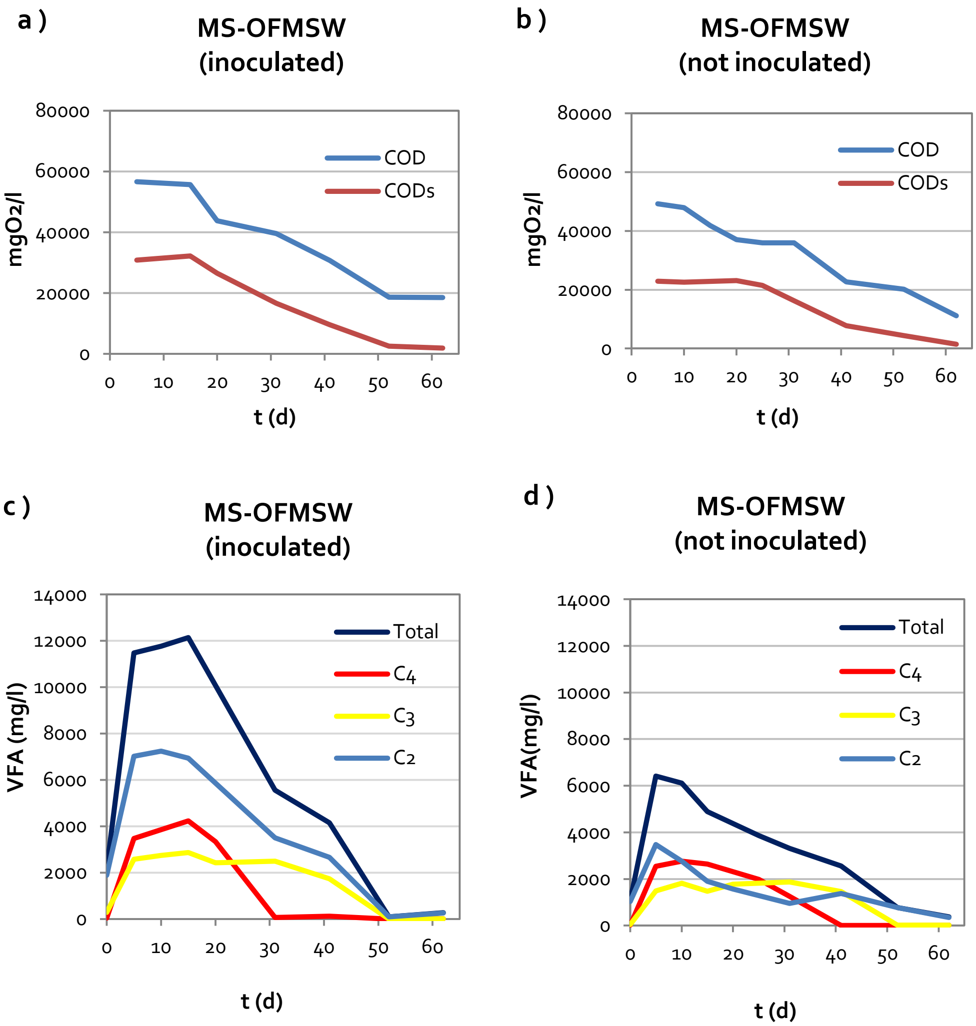

Figure 15. Chemical oxigen demand (total and soluble) in mechanically sorted OFMSW with (a) and without inoculum (b). Volatile fatty acids concentration with (c) and without inoculum (d). C2: acetic acid, C3 propionic acid and C4: butyric acid.

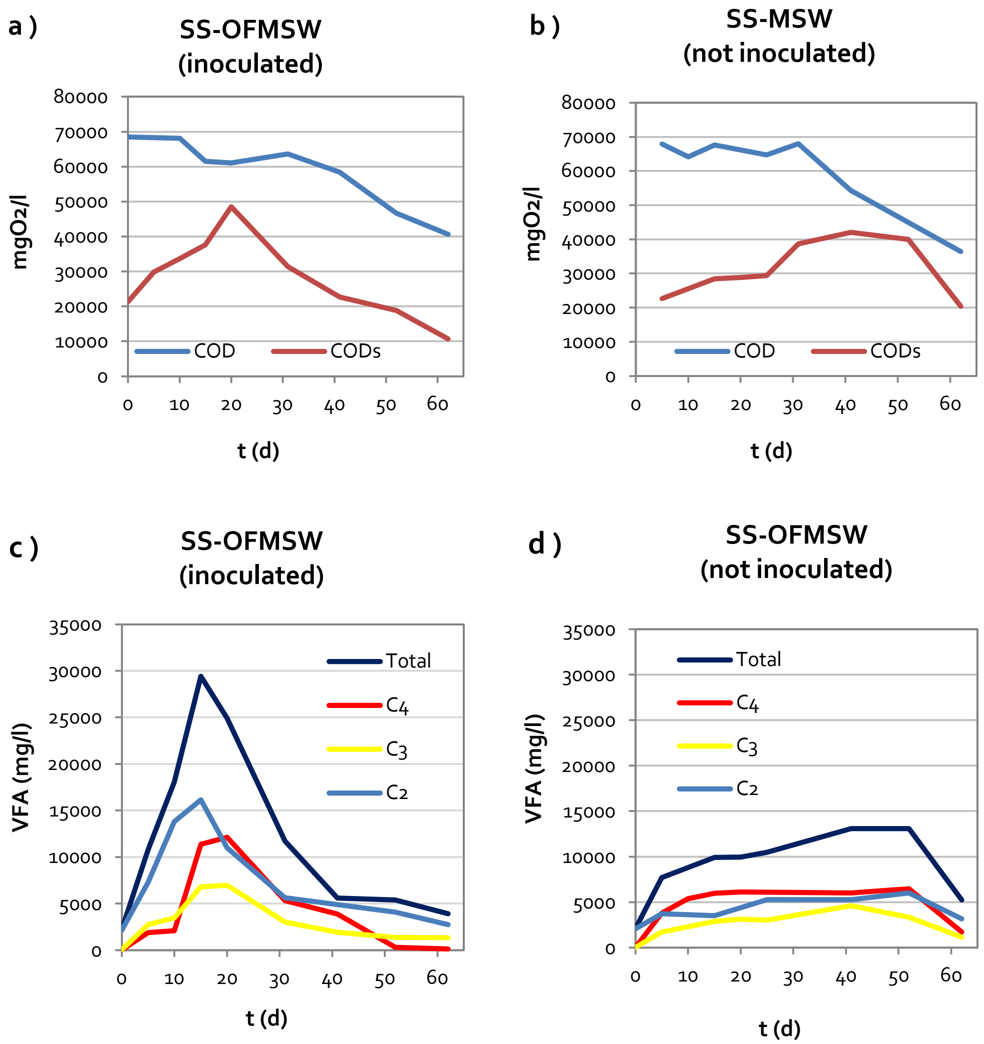

Figure 16. Chemical oxigen demand (total and soluble) in source selected OFMSW with (a) and without inoculum (b). Volatile fatty acids concentration with (c) and without inoculum (d). C2: acetic acid, C3 propionic acid and C4: butyric acid.

These conditions were set in the pilot plant installed in the laboratory with a reactor of 5 l. and 400 ml/d flow (figure 17). This pilot plant operated in continuous mode for almost 100 days simulating the start-up of commercial plants: a first stage of biomass growing inside the closed reactor for 30 days and the subsequent feeding with the final effluent, reaching high degradation rates. This method reduces the start-up time by up to 60% compared to progressive increase of the solids loading.

In the second stage, after 20 days the steady state was reached and stable composition in the effluent was obtained despite the observed changes in the composition of the influent (10 lots were needed). These changes in the influent composition (although all of them were prepared in similar conditions from existent material from one of the MBTPs) reflect the variation to which these processes are subjected by the great diverse in the raw material (table 3). However, it has been proved that a stable microbial population is able to absorb these variations and maintain a constant composition in the effluent. Organic load in the effluent was 3000 mg O2/l for influent load between 10000 and 20000 mg O2/l, that is, 90% of organic matter degradation with proportional methane production expected (figure 18). This degradation rate for the organic matter results in a production of methane up to 80L in 90 days.

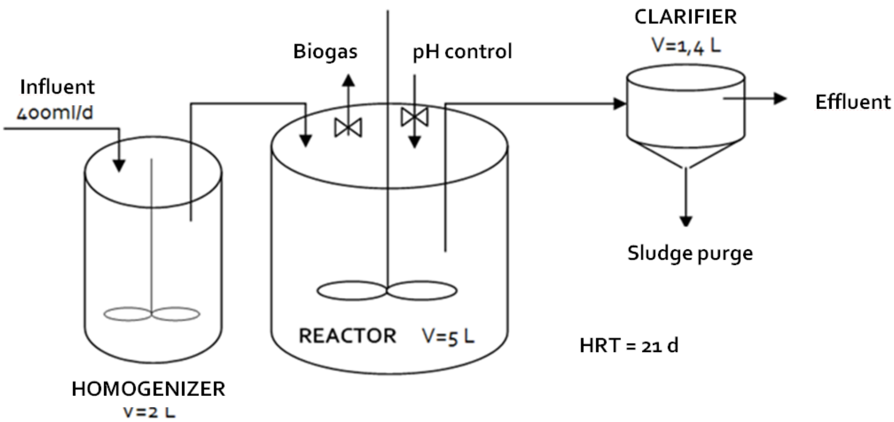

Figure 17. Operating diagram of the anaerobic digestion pilot plant scale.

For this anaerobic process, growth yield factor (Y) and rate of cell death (kd) were 0.074 mg VSS/mg COD y 0.002 d-1, respectively. While the value of the growth yield factor is within the normal range of values given in the literature, the value of the rate of cell death is lower than usual values in the literature indicating the absence of inhibitors or toxic compounds for bacterial growth in the organic fraction of waste treated.

		Influent		Effluent	
		$\bar{x}$	*s*	$\bar{x}$	*s*
Whole broth	COD (mg O_2/l)	**30244**	4686	**3388**	266
	TS (mg/l)	**21725**	3113	**5084**	230
	VS (mg/l)	**14899**	2251	**1843**	228
	ρ (g/dm³)	**1006**	9	**1008**	9
	SS (mg/l)	**9505**	1835	**1486**	324
Soluble fraction	COD sol (mg O_2/l)	**15305**	3431	**2048**	472
	TOC (mg/l)	**5013**	1030	**493**	60
	TN (mg/l)	**357**	130	**412**	79
	FVA (mg aa/l)	**2193**	986	**128**	49
	NH_4^+ (mg/l)	**178**	42	**524**	
	Cl^- (mg/l)	**858**	89	**827**	116
	NO_2^- (mg/l)	**411**	157	**342**	24
	NO_3^- (mg/l)	**96**	54	**n.d.**	n.d.
	SO_4^{2-} (mg/l)	**101**	197	**14**	2
	PO_4^{3-} (mg/l)	**208**	168	**n.d.**	n.d.

Table 3. Characterization of influent and effluent (steady state) of the plant in continuous operation. (n.d.: undetected)

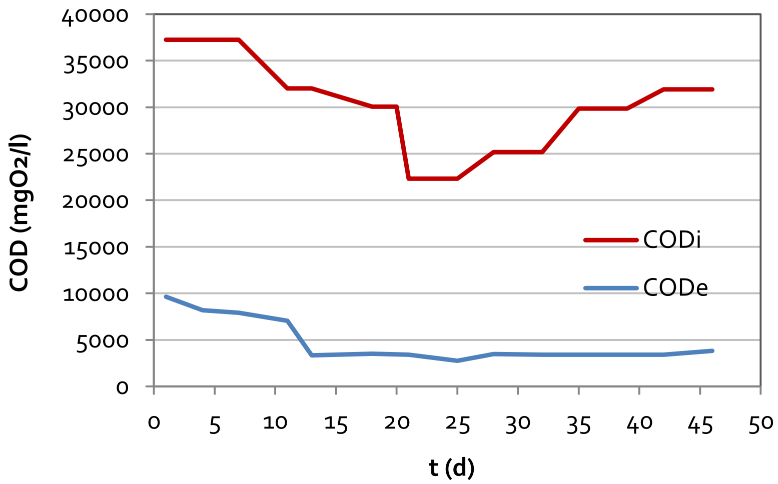

Figure 18. COD (influent and effluent) in the anaerobic digestion of MW-OFMSW.

According to the results, the anaerobic digestion of the mechanically separated organic fraction fits the Contois kinetic model with the final equation: XT/(So-Se) = 1.074 X/ Se + 0.881. The degradation rate and therefore the biogas production can be predicted from parameters as the biomass concentration (X), residence time (T) and COD in the influent (So). Kinetic parameters were obtained and compared to other authors. The specific degradation rate was found slightly faster than that used to describe the anaerobic digestion of source selected organic fraction.

The study of the waste management model in Castilla y León has been completed with a life cycle analysis (LCA). On one hand, current scenarios have been evaluated with the aim of providing an overview of the impact caused by the operation of MBTPs (figure 19). MBTPs were divided into two types for this analysis: MBTP type I where anaerobic digestion is used to produce electricity and digestate is composted, and MBTP type II where all the organic matter is stabilized by composting. The evaluation was facilitated by the software EASEWASTE according to the LCA method EDIP 1997 and included the following impact categories: non-toxic environmental impact categories (global warming – GW, photochemical ozone formation – POF, stratospheric ozone depletion – SOD, acidification – AC and nutrient enrichment – NE) and toxic environmental impact categories (ecotoxicity in soil – ETs and in water (chronic) – ETwc, human toxicity via soil – HTs, via water – HTw and via air – HTa) and spoiled groundwater resources –SGR.

On the other hand, the improvements identified during this study have been evaluated from the environmental point of view in order that these results can be used as tool to support the decision-making processes. The identified improvements are RDF incineration instead landfill (i), optimization of the anaerobic biological processes (ii) (figures 20 and 21) and optimization of recovery of recyclable materials (iii) (figure 22). Bars in these figures indicate the net difference in the environmental impact or saving between the improved and the baseline scenario. Figure 22 shows also the differences between incineration and recycling of the recovered materials.

Results of LCA showed that the activities with the greatest influence on reducing the greenhouse gases (GHG) emissions are recovery of recyclable materials, carbon sequestration in landfills and energy recovery through anaerobic digestion. However, among the proposed alternatives, RDF incineration does not seem to provide clear environmental benefits which only are evident in the global warming category if the marginal energy replaced is coal. If natural gas is the marginal energy, most realistic option nowadays in this region, RDF incineration does not show any environmental advantages over landfill in the most important category (figures 20 and 21). It is clearly positive in the rest of categories although strongest arguments would be needed to sustain this important change in the waste management at this region. For all the recyclable materials except paper and cardboard, material recovery maximization and recycling seem to be more environmentally beneficial than incineration (figure 22). Moreover in the case of paper and cardboard incineration resulted in savings only if coal is the marginal source. Significant benefits are observed from increase in the rates of recovery of recyclable materials and in the treatment of the organic matter by anaerobic digestion instead of composting. Facilities currently in operation should increase their performance also.

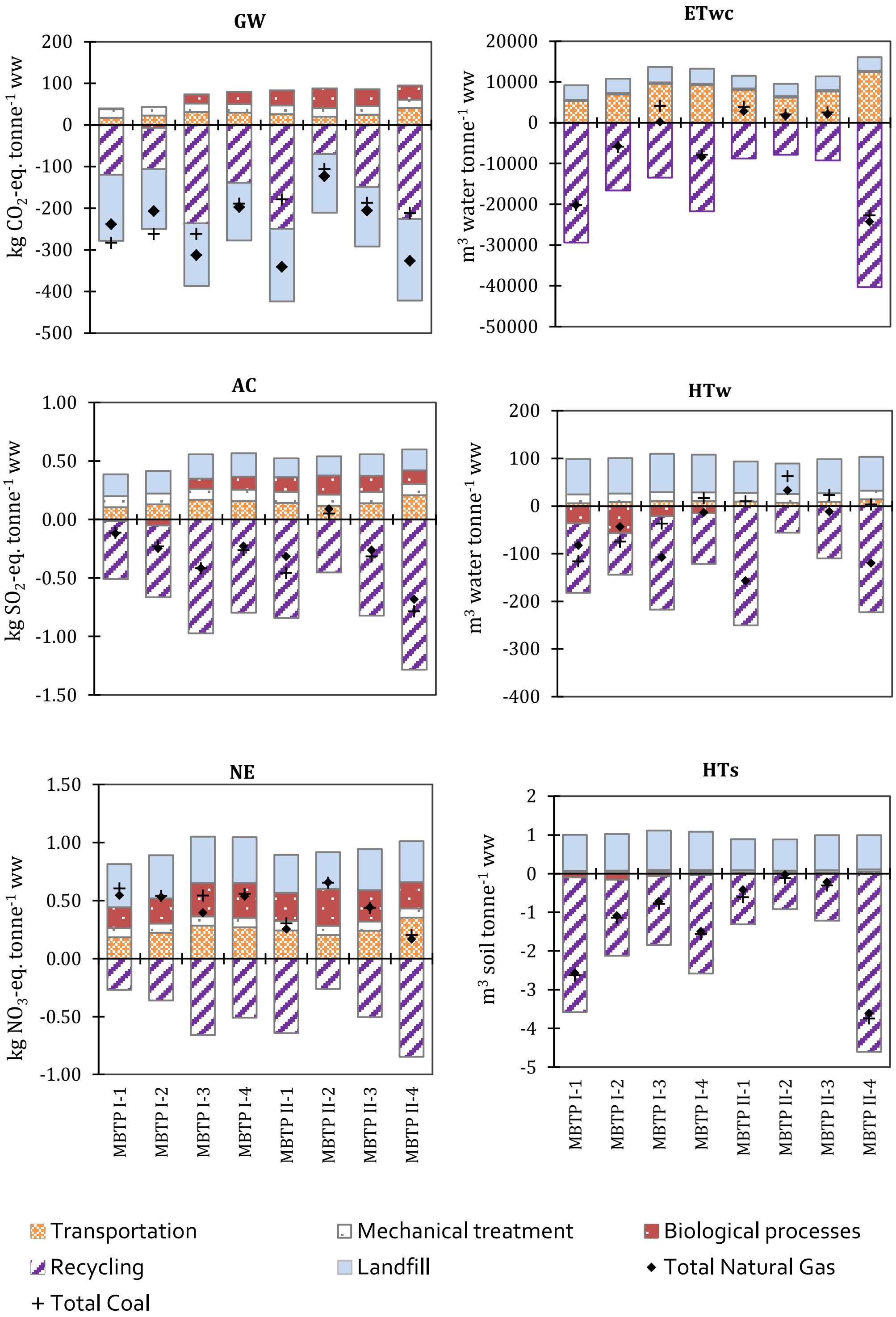

Figure 19. Characterized environmental impacts on toxic and non-toxic categories: process contributions.

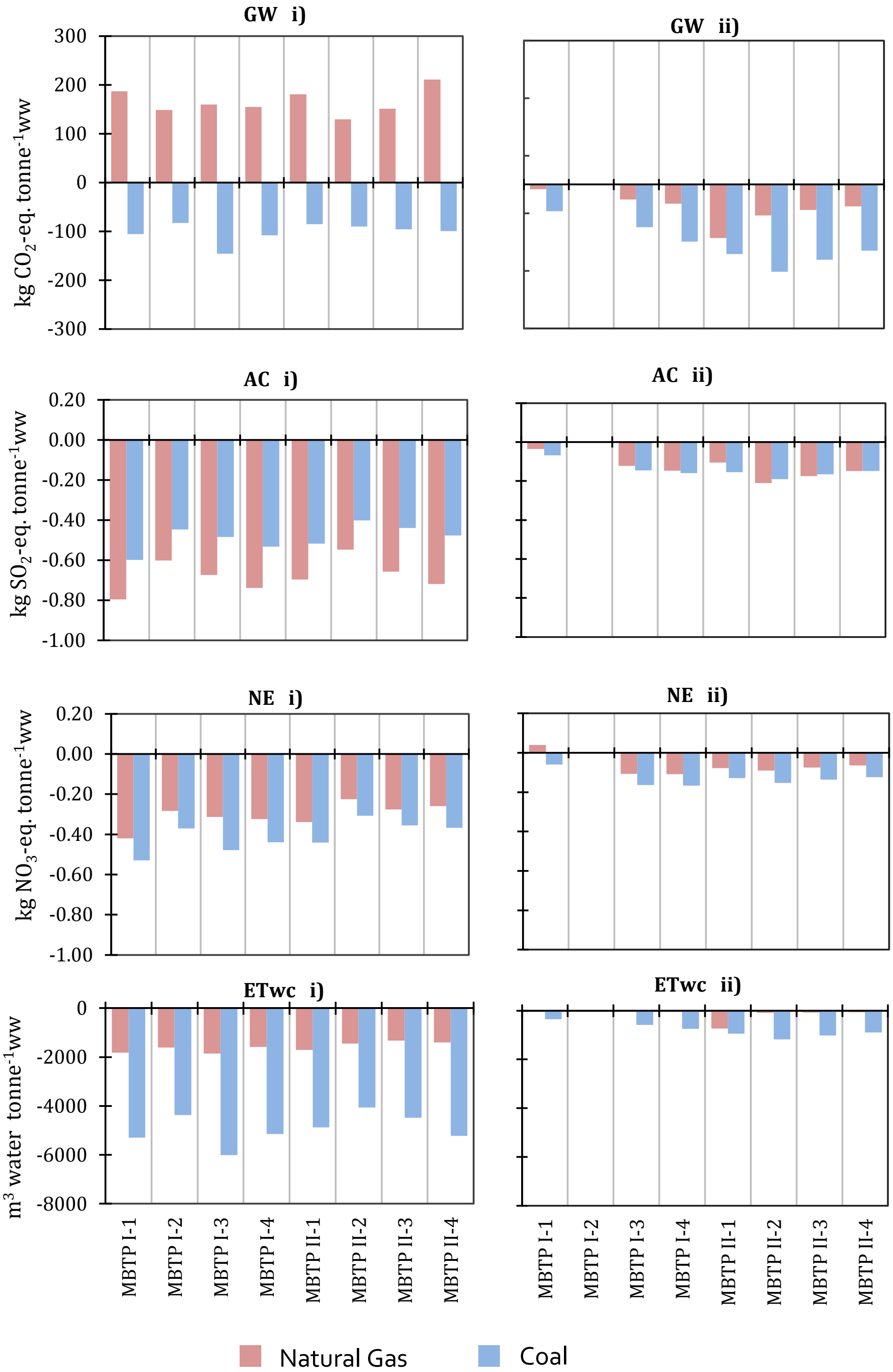

Figure 20. Environmental consequences associated with the potentially improved waste management scenarios (i and ii). Non-toxic categories

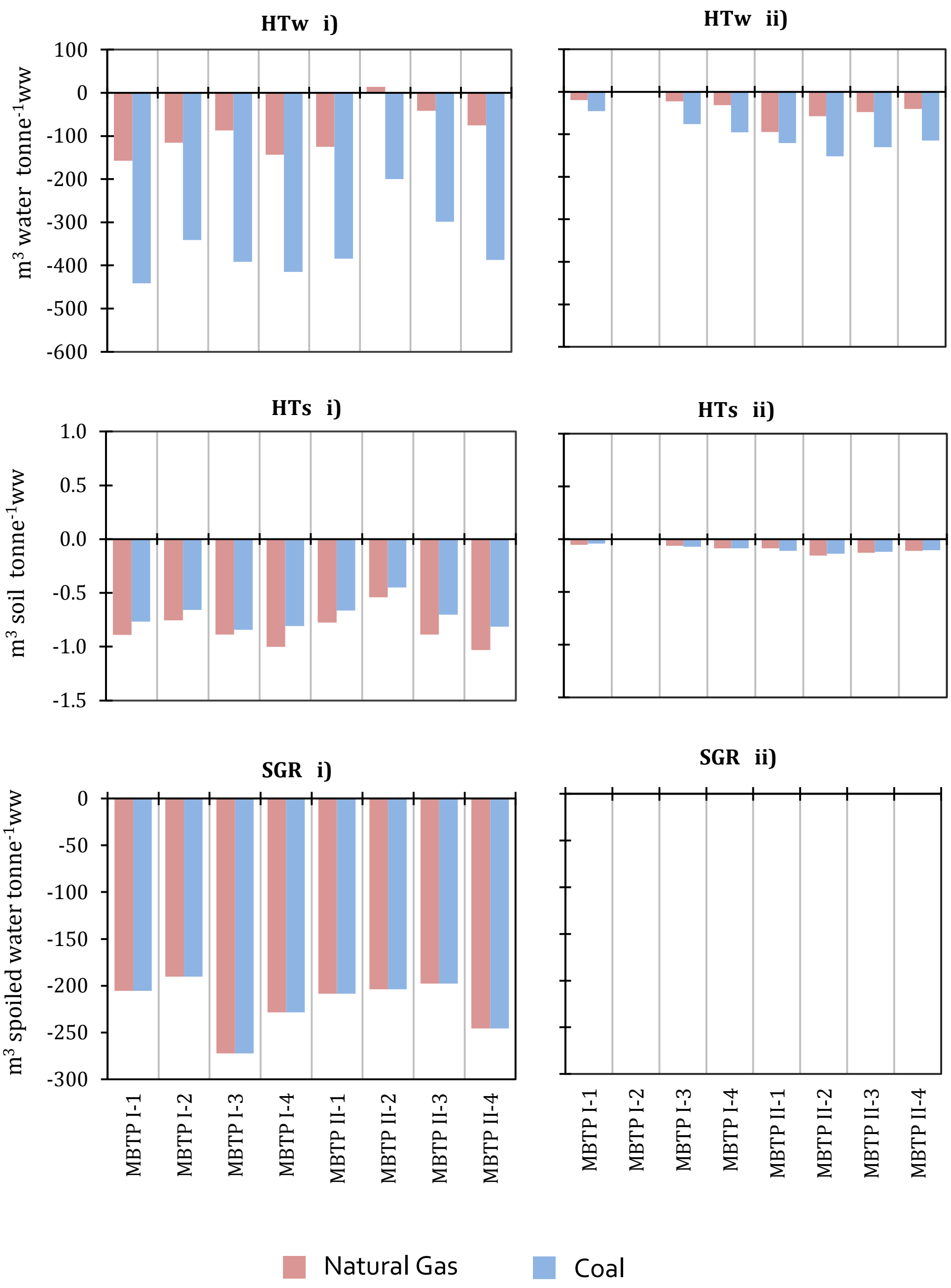

Figure 21. Environmental consequences associated with the potentially improved waste management scenarios (i and ii). Toxic categories

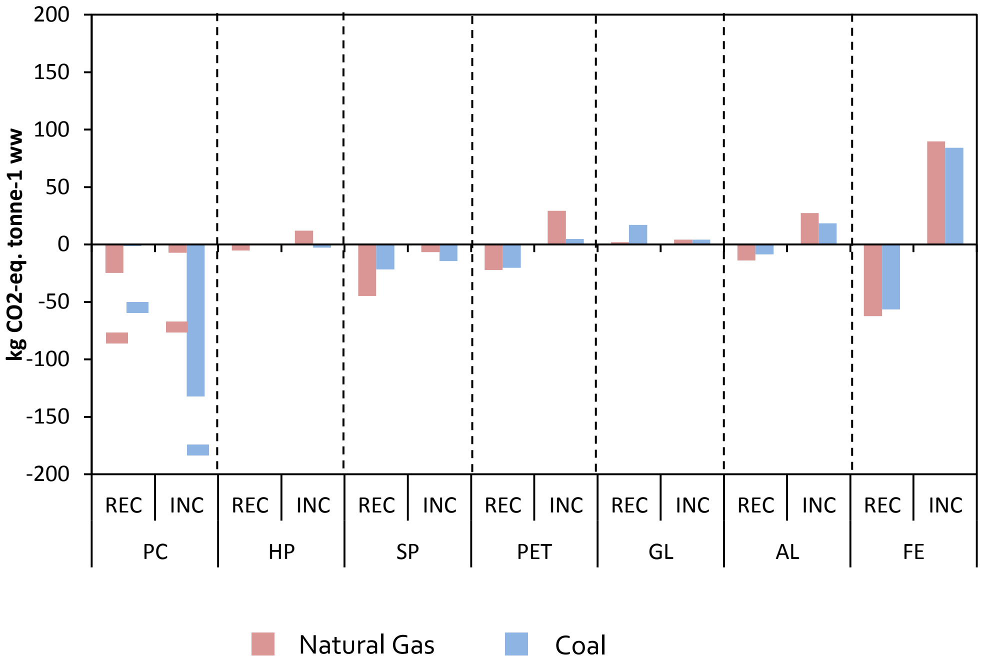

Figure 22. Paramount average GHG savings (kg CO_2-eq. tonne-1 ww) associated with 100% waste material recovery at the MBT or, alternatively, 100% waste material incineration, relative to the baseline LCA results.

Finally, as main conclusions of this research work, it can be said that a number of key points where the waste management model of this region can still be improved have been identified. It has also increased the level of knowledge of composition and the most important characteristics of all the streams involved in a MBTP, inputs and products after mechanical and biological treatments. This allows identifying a number of proposals for further improving the performance of these processes which is still far from optimal because of, among other things, great heterogeneity in the composition of raw materials. Because of the household waste nature, their composition cannot be controlled. Recommendations arisen after finalizing this work have been shared with major players involved in the waste management; some of them can be immediately implemented. According to these results, to optimize the performance of both operating plants and new construction ones, it must: i) optimize the recovery of recyclable materials through greater sorting automation, ii) prioritize the anaerobic digestion with electricity production instead of aerobic composting, iii) improve the yield of anaerobic digestion with better control of the process and an increase in the reuse of waste heat and iv) increase the quality of biostabilized material before using it as organic amendment primarily through improvements in the refining stage.