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Comparison of compostable bags and aerated bins with the traditional storage systems to collect the organic fraction of municipal solid waste at home. The case of Catalonia as example

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Abstract

The separation of biowaste at home is a fundamental step to improve, facilitate and reduce the operational costs of the further treatment of organic municipal wastes. Typically, the traditional method to collect separately these wastes at home has been carried out using a sealed bin with a plastic bag. Today, the use of modern compostable bags is starting to be implemented in society at some European countries. These bags are composed of biodegradable polymers that are mostly based on renewable resources. In addition to the use of compostable bags, a new model of bin is also promoted, which has the most part of its surface perforated and jointly with the compostable bag makes the so-called "aerated system". In this study, different combinations of home collection systems have been systematically studied at laboratory and at home. Quantitatively, the results obtained demonstrate that the combination of aerated bin and compostable bag is an effective system to improve the collection of biowaste without significant gaseous emissions and to prepare the organic waste for a further composting process as observed from the respiration indices. In terms of weight loss, temperature, gas emissions, respiration index and organic matter reduction, the best results were achieved with the aerated system. At the same time, a qualitative study of these combinations has been carried at the home of 100 families. Finally, more than 80% of these families preferred the aerated system.

Keywords: aerated bin; compostable bag; waste collection systems; composting; organic fraction of municipal solid waste.

1. Introduction

The Organic Fraction of Municipal Solid Waste (OFMSW) or biowaste is mainly composed of food rejects from vegetable or animal origin and small pieces of green wastes. These wastes need to be separately collected at home to be biologically treated through composting or anaerobic digestion, according to the new European regulations to ensure the production of high quality compost.

Catalonia, a well-developed region in the north-east of Spain is implementing an overall system of source-separated collection of the OFMSW all over the Catalan territory. The last study about the municipal waste composition in Catalonia was carried out during the period 2004-2005 and showed that the OFMSW jointly with several typologies of green wastes were 36% (32% and 4%, respectively) of the total weigh of collected municipal wastes. More generally, in Spain about 23 millions of t of MSW were collected in 2004. 2.3 millions of t of this overall MSW stream were separately collected and 262,221 t were composted and 323,896 were anaerobically digested (Spanish Ministry of Environment, 2008). In Catalonia, it is estimated that about 40% of the MSW are collected with some system that implies separation at home, mainly street bin or door-to-door systems. Specifically, 318,354 inhabitants (about 4% of the total population) have access to a door-to-door collection system, which means that 55,770 t of biowaste could be collected with this system (Giró, 2006).

The management of the OFMSW (including collection and processing) should be carried out as soon as possible and under conditions that minimize the presence of leachate and odours due to the particular characteristics of the OFMSW such as a high density, moisture and putrescibility. In 1993, Catalonia started the first experiences with the separate collection of the OFMSW and it has been gradually implemented everywhere. Since then, the collection system has been continuously analyzed and improved. Currently, different systems are used to collect biowaste: door-to-door and street containers are the most typical. In any case, both systems have the same starting point, the first step of separation at home, where a bag in a bin with a total capacity of 10 L is commonly used. Traditionally, low density polyethylene plastic bags (LD-PE) have been used to collect the OFMSW. Most of plastics that arrive at the composting plants as impurities correspond to the bags used to collect and dispose the OFMSW (Huerta-Pujol et al., 2010). As polyethylene is not biodegradable, the presence of these bags results in a problem during the composting process and makes the pre- and post-treatment more difficult (Körner et al., 2005). To avoid this problem, local administrations are now recommending the use of compostable bags that are composed of corn or potato starch. The physical deterioration and biodegradation of these bags can be completely achieved after six days (Mohee and Unmar, 2006).

In recent years, a new system to separate the organic wastes at home has been introduced. This system, known as “aerated system”, comes from northern Europe. It is based on the use of a perforated bin combined with the use of compostable bags. Thus, the aeration of the OFMSW is improved and the weight reduction of waste due to water evaporation is highly promoted. The continuous air exchange between the waste and the environment allows the reduction of unpleasant odours, which are one of the most reported complaints about the OFMSW separation at home. Moreover, the aerated system increases the mechanical resistance of the compostable bag by drying the bag surface.

The improvement of the OFMSW quality due to the generalized use of compostable bags could have a notable influence on municipal waste management, since its treatment cost often depends on the percentage of impurities of the source-separated fractions. In general, the waste taxes are used to optimize the municipal solid waste management and to improve the biological treatment of the OFMSW to obtain biogas and/or high quality compost. For instance, in Catalonia, a specific tax is applied to any municipal waste that is finally disposed in a landfill or burned in an incineration plant (10 € t^{-1} and 5 € t^{-1}, respectively) without previous separate collection (*Agència de Residus de Catalunya*, 2006). The tax refund is returned to compensate the municipalities for the cost of source-separated collection and for the maintenance of existing plants and construction of new biowaste treatment plants (using biological process such as composting, anaerobic digestion or the combination of both). Specifically, in Catalonia, part of this tax is returned to the municipalities and it is calculated according to the quality and quantity of the separated collection of the OFMSW. Obviously, the final value of returned money is also highly dependent on the people's participation in the separation of source-separated collection system, which could presumably increase with the use of the aerated system since they results are more satisfactory for the population. In any case, the economic results of implementing this aerated system for a municipality depend on all the abovementioned factors and need a deep analysis.

From the Life Cycle Assessment (LCA) point of view, a large number of processes are included for waste management systems. Literature reports many studies on LCA of solid waste management and/or treatment processes (Blengini, 2008; Banar et al., 2009). In this framework all the data obtained in the storage of the OFMSW at home can help to undertake a more complete LCA on the overall process of waste management.

Therefore, the main goals of this work are: i) to determine the efficiency of the different combinations to separate the OFMSW at home (aerated or non-aerated bin and compostable or non-compostable bag) using quantitative data on the characteristics of organic matter found in each system, ii) to study the use of the compostable bags in society and its repercussion on the impurities content of the OFMSW by implementing all the storage systems available for the collection of OFMSW at home and iii) to estimate the economic viability of the aerated system for municipalities.

2. Materials and Methods

2.1. Bins

Two different types of bins have been used in this study. The first one is the typical closed bin. Normally, this bin has a rectangular geometry with a total capacity of 10 L and it is totally closed. Figure 1 shows an image of the typical non-aerated bin used at home together with the aerated bin. Both bins have the same total capacity and geometry.

2.2. Bags

LD-PE (referred as plastic), compostable biopolymers (Mater-Bi® product) and paper have been the materials of the bags considered in this study to collect the OFMSW. Table 1 shows the main properties and general characteristics of these different bags. At present, the plastic or non-compostable bag (nCB) is still the most widely used in Catalonia. The compostable bags (CB) are made from the synthesis of biopolymers obtained from natural resources, which can be biologically degraded. Specifically, the compostable bags used in this study were made of corn starch. The paper bags (PB) are obviously fully biodegradable but they have resistance problems when wet wastes and/or excess weight are collected. Unlike plastic bags, which are made of fossil fuels, the raw materials of compostable and paper bags are obtained from crops. The images of the three type of bags above described are shown in Figure 2.

2.3. Experimental design at laboratory

All the possible combinations among the bins and bags described were studied, i.e. (i) aerated bin with compostable bag (AB-CB), from now on the aerated system, (ii) aerated bin with non-compostable bag (AB-nCB), (iii) non-aerated bin with compostable bag (nAB-CB) and (iv) non-aerated bin with non-compostable bag (nAB-nCB). Triplicates of all these tests were carried out in the laboratory. One more sample of the combination (i) was also placed outdoors, since sometimes the bin of the OFMSW is placed outside. To study the use of the paper bag (PB), one more assay was included (in duplicate) only with the aerated bin (AB-PB).

Once the combinations were defined the experiments were carried out as follows:

- A quarter part of the total capacity of each bin was daily filled with the OFMSW. After the fourth day the bins were totally filled. Therefore, it was considered that the experiment was finished. Only the bin placed outdoors was monitored until the seventh day without adding more waste.
- Every day the raw waste added and the weight value after a 24-h period were measured to know the weight loss of each combination. Temperature was also monitored. This measure was determined in the centre of the solid material using a temperature probe (Pt-100, Desin Instruments, Barcelona, Spain). Additionally, the oxygen concentration was also measured inserting an oxygen sensor (Lutron 5510, Lutron Co. Ltd., Taiwan) in the centre of the organic matrix, where the minimal concentration of interstitial oxygen was observed.
- The concentrations of four specific gases (methane, N_2O, ammonia and total Volatile Organic Compounds (VOCs)) were daily determined in each bin. To determine the gas concentration, each bin was isolated during 30 minutes in a cylindrical container of a total volume of 30 L. Afterwards, the gas around the bin was sampled in a Tedlar® bag and analyzed by gas chromatography as explained and reported in Cadena et al. (2009a).
- To finish the study, the material obtained in each experimental combination was analyzed. Moisture, organic matter content and respirometric assays were undertaken. These three parameters were also determined in the initial sample of the OFMSW.

2.4. Home experiments

A hundred families of four Catalan municipalities were responsible for testing the four possible combinations among compostable and non-compostable bag and aerated and non-aerated bin with the organic wastes that each family generated at your home. The families were asked to test all the combinations in the complete use of each system: filling the bin several times, observing leachate production and detecting unpleasant odours, as well as the performance of each bag tested. These families were voluntary people from each of the municipalities participating in the study, which were selected to be in each of the four provinces of Catalonia (Barcelona, Tarragona, Lleida and Girona). Finally, 25 families were selected from a large number of volunteers for this study. These families were selected trying to include several typologies: marriages, marriages with one or two children and old people who live alone. The experiment using the different combinations of bin and bag was carried out during eight consecutive weeks by a study team of four people who filled a complete questionnaire after visiting each of the family participating in the study once a week. Every two weeks only one combination was tested. Several qualitative aspects such as separation incidents, resistance of bags, odour detection and general level of satisfaction were recorded after each period of two weeks when one combination had been tested.

2.5. Organic Fraction of Municipal Solid Waste (OFMSW)

The used OFMSW to carry out the laboratory experiments was collected from the *Mancomunitat de la Plana* composting plant (Malla, Barcelona, Spain) the same day of starting the assays. The OFMSW comes from a door-to-door collection system. In the home experiments the OFMSW used was composed of the organic wastes produced by the families.

2.6. Analytical Methods

Water content, Dry Matter (DM) and Organic Matter (OM) content were determined according to the standard procedures (The US Department of Agriculture and The US Composting Council, 2001).

To obtain the Dynamic Respirometric Index (DRI), microbial respiration was measured as O_2 consumption in a dynamic respirometer built and started-up by Ponsá et al. (2010), which was based on the methodology described by Adani et al. (2006). The DRI represents the average oxygen uptake rate during the 24-h period of maximum biological activity observed during the respirometric assay (normally, it is achieved between 24 or 48 hours after starting the test) and it reports the material stability degree (Adani et al., 2004; Ponsá et al., 2010). It is expressed in mg of O_2 consumed per g of organic matter (or dry matter) per hour and measured in triplicate assays.

As previously commented, the monitored gases (methane, N_2O, ammonia and VOCs) were analyzed following the methods developed and started-up by Cadena et al. (2009a).

2.7. Economic balance

The economic balance was estimated by relating the experimental difference found between the weights of the OFMSW collected per year through the aerated (AB-CB) and the traditional system (nAB-nCB) and considering the wastes tax refund and the OFMSW treatment cost. The balance presented in this work shows the results for a municipality of 4999 inhabitants (small-size municipality) with a door-to-door collection system, as example, and assuming an average value of the OFMSW collected of 0.332 kg inh^{-1} day^{-1}. The data and local prices necessary to calculate the economic balance were provided by the Catalan Waste Agency (*Agència de Residus de Catalunya*, 2009; 2010).

In the year 2010, part of the tax of MSW disposition in landfills or incineration plants was assigned to the source-separated OFMSW treatment and to improve the selective collection of this fraction, both points as tax refund for the municipalities. This refund is calculated as a function of two points. Regarding the OFMSW treatment, the municipalities that deliver the source-separated OFMSW in a biological treatment facility receive 33.5 € per tonne of waste. Regarding the OFMSW separated collection, the quality of the OFMSW treated with biological treatments is encouraged by means of two correction factors that multiplies a standard value assigned to the collection of one t of the OFMSW (8.6 € t^{-1}). One factor (Z) depends on the number of inhabitants (1, 1.28 or 1.5 for a number of inhabitants over 50000, between 5000 and 50000 and below 5000, respectively). The other correction factor (Y) is calculated according to the impurities content of the OFMSW collected using the equation: Y=-0.1X+2.5, where X is the percentage of impurities (in total weight). In general, the equation that describes the tax refund is the next (equation 1):

$$\text{Tax Refund} = \text{Weight collected (t)} \cdot 33.5\ € \ t^{-1} + \text{Weight collected (t)} \cdot 8.6\ € \ t^{-1} \cdot (Z+Y)$$

(Equation 1)

On the other hand, the OFMSW treatment prices are also calculated as a function of the impurities content and the total weight collected. Table 2 presents the list of prices used in Catalonia during 2010.

In order to compensate the possible negative balance that the weight reduction of the aerated system can produce (minor weight collected means a reduction of the treatment cost and of the tax refund), an increase of the citizens' participation must be assumed. In this case, the increase of the source separation of OFMSW collected provokes a decrease of the total waste disposed in the landfill. Accordingly, the savings in the landfill cost must also be considered in the economic balance. The landfill cost is an average value of 40 € t^{-1} plus a tax of 10 € t^{-1}.

3. Results and discussion

3.1. Laboratory experiments

3.1.1. Weight losses

The cumulative weight reductions of the OFMSW obtained in the six combinations studied is shown in Figure 3. The evolution of the experiment placed outdoors was followed during seven days, while the other ones were followed during four days. Results are presented as the average value of the replicates (except for the study performed outdoors, where only one experiment was monitored). As can be observed, the aerated bin combined with the paper bag presented the highest weight reduction. However, the paper bag was rapidly discarded as a result of its low resistance to moisture and a rapid deterioration. It seems evident that even with the aerated bin these bags are not suitable for the OFMSW collection at home due to their low mechanical resistance with a wet material such as the OFMSW. Without considering the paper bag, the combination with the highest weight reduction was the indoor aerated system that achieved a total weight reduction of 5%. Simultaneously, after four days the weight reduction of the outdoor aerated system was only 3%. Non-aerated bin in combination with compostable bag presented an overall reduction of 2%. Finally, all experiments with non-compostable bags had practically negligible weight reductions (<1%).

3.1.2. Temperature monitoring

Figure 4 shows the evolution of temperatures during the experimental monitored period. In order to determine the influence of the external conditions on the bin temperature, the environmental and laboratory temperatures were also recorded. As can be observed, the laboratory temperature was around 20 ºC during the first two days; afterwards it decreased 2 ºC. The environmental temperature was more or less constant at 17 ºC until the fourth day of study. From this day, the environmental temperature decreased considerably. The last temperature value recorded was below 14 ºC.

All the experimental bin temperatures were within the range of 20 to 30 ºC. In general, excluding the combinations with non-aerated bins, a clear relationship between the bin temperature evolution and the external temperature was not observed. However, a considerable change in the external temperature can affect the bin temperature, as it occurred at the end of the outdoor experiment.

The temperature profiles showed that the indoor aerated system favoured the composting conditions. It could be suggested that the composting process started by itself in the bin due to the high temperatures maintained during the experiment. The results obtained for the outdoor aerated system showed a similar maximum temperature than the one of the indoor system, although its evolution was different from the rest of aerated bin experiments. After starting, the temperature profiles of the aerated bins increased. Contrarily, in the outdoor aerated system the temperature only increased from the third day. It can be hypothesized that this was due to the difference between the laboratory and the environmental temperatures. From the fourth day, the temperature of the outdoor experiment decreased approximately 10 ºC. The material compaction and the environmental temperature decrease were probably the causes for this decrease.

Nevertheless, these results must be carefully interpreted because the temperature observed in the bin is directly related to its volume, which in this case was 10 L. For larger volumes, organic matter tends to accumulate heat and higher temperatures are to be expected as shown in previous results (Barrena et al., 2006).

3.1.3. Gaseous emissions

Table 3 shows the emissions profiles of the gases considered (methane, ammonia, N_2O and VOCs) for each experiment. The gaseous emissions are expressed as mg of gas compound emitted per hour and in form of cumulative emissions for each gas. In general, lower gaseous emissions were obtained when the values were compared to the industrial and home composting processes, although this fact can be a consequence of the different ranges of temperature and pH observed at full-scale (Cadena et al., 2009b; Colón et al., 2012). When emissions are equal to zero, it implies that a similar concentration level of each pollutant was found in atmospheric air when compared to the bin surrounding air. In some cases, the emissions of the gases analyzed were close to this threshold. In any case, taking into account that the NH_3 measures were always below 17 ppm_v (odour threshold), the best combination should be considered as a function of the environmental impact of CH_4 and N_2O as CO_2 equivalents: 25 kg_{eqCO2} and 296 kg_{eqCO2}, respectively (IPCC, 2006). Adding the CO_2 equivalents of CH_4 and N_2O for each combination the results showed that no significant differences were observed (data not shown).

Unfortunately, no literature values have been found to compare the values found in this study with similar systems. However, the data presented in this work could be useful to undertake an overall Life Cycle Assessment on the OFMSW management and treatment.

3.1.4. Respirometric Indices, dry matter and organic matter content

Initial values of Dynamic Respirometric Index (DRI), dry matter and organic matter content of the OFMSW collected are shown in Table 4 jointly with the final values obtained for each combination of collection system tested. In most cases, the DRI increased after the experiments. This could mean that after the separation at home the composting process already starts. This is a typical observation of composting process where the value of the initial DRI is usually lower than the value of this index during the initial moments of the OFMSW decomposition (Ruggieri et al., 2008).

The most significant increase of DRI was observed using compostable bags, except for the outdoor aerated system, which produced the lowest value. In addition, high DRI values obtained with the use of compostable bags were only statistically different from the initial DRI value. The low DRI of the outdoor aerated system was probably due to the final low temperature found in this system. In fact, the exterior temperature effect on the DRI is not known. Since no exterior experiments at higher environmental temperatures were undertaken, it can be hypothesized that the microbial populations responsible for the biodegradation needed a higher adaptation period when the temperature is considerably low as it is important to note that the DRI is a single measure of the biological activity at 37ºC (Ponsá et al., 2010).

On the contrary, the differences in the dry matter and organic matter contents for the samples at the beginning and at the end of the experiments were no statistically significant. In conclusion, both parameters cannot be used for the study of the material evolution in such a short period of time and the use of DRI seems more adequate.

Additionally, in other similar experiments (data not shown), the monitoring of the interstitial oxygen percentage in the waste in several days was followed. In general, a gradual decrease of the oxygen percentage was observed in all the combinations studied (AB-CB, AB-nCB, nAB-CB, nAB-nCB). After two days, the non-aerated bins registered an oxygen level close to 11%, whereas an oxygen content of 18% was measured in the aerated bins. From the fourth day, all measures were below of 5%. At the end of the experiment, AB-CB combination showed that the aerated system maintained the highest oxygen levels although these values were always low (around 3%) when compared to the air level (20.9%). In the other cases the oxygen measures were below 1.5%. This is another indication of a high activity in the aerated system without oxygen limitations.

3.2. Home experiments

The qualitative monitoring of the home experiments was basically focused on practical aspects such as the bin location at home, the characteristics of the wastes collected, storage time at home, satisfaction level (odours, bag resistance, etc.), personal opinions about the best system and why, among others.

After the experience with the several combinations of the collection systems tested, the same survey was sent to all the project participants. All the families participated in the full experiment and none of them drop out. The general results showed that the aerated system was the most satisfactory combination. However, some incidences with this system were also commented. The most frequent incidences reported were the apparent fragility of the compostable bag, an insufficient bag size and the difficulty to remove the bag from the bin and to tie it up. Some participants expressed doubts about the behaviour of the aerated system with higher ambient temperatures that were not reached during this set of experiments, although the study was undertaken in a relatively warm season (from April to June of 2010 when the recorded temperatures were within 10 to 25 ºC). At the end of the experience, 85%, 90%, 80% and 80% of the people of each municipality preferred the aerated system. The percentage of incidences using this system (mainly related to the apparent fragility of compostable bags and an insufficient bag size) were around 10% of the participating people. No incidences were reported on the detection of unpleasant odours, leachate or bag breaking in the case of the aerated system.

On the contrary, severe problems of leaching and the presence of condensates where reported with the non-aerated bin, which seemed incompatible with a compostable bag that in most cases was highly deteriorated because of moisture excess and wetting. In the case of plastic bags, there was no bag deterioration, but the problem of leaching and condensation of moisture, which finally resulted in odour problems, still remained.

3.3. The use of compostable bags

One positive aspect of the use of compostable bags to carry out the source-separation of the OFMSW is that their use is parallel to an information campaign on the benefits of waste separation at home. In Catalonia, the available data obtained from the Catalan Waste Agency (*Agència de Residus de Catalunya*, 2009) confirmed these benefits. In summary, the mandatory use of the compostable bag in door-to-door collection systems resulted in the lowest level of impurities (1.54%, Table 5), whereas when the compostable bag use was not mandatory the level of impurities was six times higher. Collection systems based on street containers also showed a significant reduction of impurities percentage when the use of compostable bags was introduced (4.61% vs. 12.06%, Table 5).

The OFMSW with such low presence of impurities can be treated in composting plants technologically simple, with low investment and operating costs since some specific equipment to remove and manage impurities may not be necessary. Moreover, the absence of impurities can help in implementing community composting, as it is described in some north-European countries (Pires et al., 2011).

Finally, some aspects about the presence of compostable plastics in compost must be commented. Klauss and Bidlingmaier (2004), in their study about the compostable packaging materials, concluded that the biopolymer addition to organic waste did not affect the compost quality and it is application for agricultural purposes. Moreover, Nakasaki et al. (2000) found that biodegradable plastic can be used as 'acid reservoir', which means that it is not acid itself but it degrades and releases acid intermediates during the composting process, which can partially avoid some part of the ammonia emissions observed during the composting process and part of the cost of treating these emissions (Pagans et al., 2005).

3.4. Economic viability of the aerated system for municipalities

At present, different taxes are being revised and established to regulate the waste collection and treatment for municipal solid wastes in the international context. When organic matter from municipal wastes is considered, it is evident that both the quantity and the quality of these organic materials are crucial to determine the final cost treatment, especially when biological processes are implemented. Specifically, in Catalonia, part of the tax that is applied to each t of municipal solid waste that is disposed in a landfill or burned in an incineration plant without previous source-selection is returned to the Catalan municipalities where the organic fraction is collected separately and treated in biological waste treatment plants, in an attempt to force all the municipalities to implement such source-separated collection systems.

From the economic point of view, it is not clear if the implementation of the aerated system at home would be favourable for all the municipalities. As it has been determined in this study, the aerated system favoured a higher weight reduction and a lower impurities percentage. These two combined facts imply that after replacing the traditional system (nAB-nCB) by the aerated system (AB-CB), the economic balance of the municipalities can change and must be analyzed in detail. On one hand, the weight reduction will imply less return of the tax but again it is necessary to calculate this weight reduction if other bin volumes are used, since the temperature profile would be different and this obviously affects the resulting weight reduction. On the other hand, the tax refund can increase because of the impurities reduction (in the case of aerated bin) and the higher participation in the source-separation collection programmes as people show a higher level of satisfaction using the AB-CB system. Therefore, the economic balance is not straightforward for each municipality.

For instance, assuming a total collection of the OFMSW with the traditional system of 606.55 t $year^{-1}$ as calculation basis (it corresponds to a case of a small-size municipality) and assuming that after 3 days the weight reduction through the aerated system is around 4.3% (Figure 3), the results of the economic balance after implementing the aerated system confirmed a slightly negative difference (-353.97 € $year^{-1}$, Table 6). To solve this problem it is necessary an increase of the citizens' participation to compensate this weight reduction that the aerated system produces because it appears a new parameter in the economic balance, which is the reduction of landfill or incineration cost (Table 7). Specifically, for the case analyzed the source-separated collected OFMSW should increase only from 0.332 to 0.335 kg OFMSW inh^{-1} day^{-1} i.e., 0.93%. According to the level of satisfaction associated to the aerated system, it is reasonable to predict that the participation will increase with this system after an informative campaign, where the optimal characteristics and benefits of the aerated system are detailed. In fact, the aerated system is replacing other traditional systems used in Catalonia used for the collection of OFMSW although, no official data are available. Nevertheless, further research and implementation monitoring of this system should confirm these points.

4. Conclusions

The aerated system (aerated bin with compostable bag) permits to reduce part of the moisture of the OFMSW due to the breathability of these bags and the bin holes. This implies that less waste has to be collected.

Different weight reductions were detected in all the combinations of bins and bags studied. The highest weight reduction was obtained in the aerated system (5% after four days). On the contrary, the lowest weight reductions were measured in non-aerated bins: 1.0 % and 0.8% in combination with compostable and non-compostable bags, respectively.

Temperature, interstitial oxygen and dynamic respiration index determined in the aerated system demonstrated favourable conditions for the biowaste storage at home.

The gaseous emissions around the bin were studied. The data presented in this study could help to undertake a complete Life Cycle Assessment considering the separation of organic wastes at home as the first step.

From the home experiments it can be concluded that there was a high level of citizens' satisfaction after using the aerated system. Typical negative issues related to the storage of organic matter at home (bad odours, leaching, flies, etc.) were not detected.

The economic estimation of the fully implementation of the aerated system according to the Catalan taxes on waste disposal showed a slightly negative result for the municipalities tax refund. However, the increase in the participation of the source-separation of organic matter due to the higher level of satisfaction and the absence of the above-mentioned problems with the aerated system should easily compensate this slightly negative result.

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Tables

Table 1: Characteristics of plastic, compostable and paper bags to collect the OFMSW at home.

	Plastic bags	**Compostable bags**	**Paper bags**
Raw material	Fossil fuels	Specific crops	Wood
Biodegradability	No	Yes	Yes
Compostability	No	Yes	Yes
Breathability	Low	High	Very high
Visual inspection of wastes	No	Yes	No
Mechanical resistance	+++	++/+	+/o
Sealing	+++	+++	++/--
Manipulability	Good	Good	Difficult
OFMSW contaminant	Yes	No	No
Storage space	Low	Low	High

where: +++: high; ++: normal; +: low, o: very low and --: inexistent.

Table 2: Average treatment cost of the OFMSW treatment as a function of its content of impurities in weight percentage (in € t^{-1}) (*Agència de Residus de Catalunya*, 2009; 2010).

Impurities (%)	0<%≤5	5<%≤10	10<%≤15	15<%≤20	20<%≤25	25<%≤30	30<%≤35	35<%≤40
Cost (€ t^{-1})	41.27	45.65	49.41	52.25	58.08	63.31	73.76	74.52

Table 3: Gaseous emissions detected expressed as rate emission (mg of contaminant emitted per hour). Total cumulative emissions are also indicated in mg.

Combination*	**day 1**	**day 2**	**day 3**	**day 4**	**Total**	**day 1**	**day 2**	**day 3**	**day 4**	**Total**
	CH_4 (mg h^{-1})				**(mg)**	**VOC (mg h^{-1})**				**(mg)**
AB - CB	0.00	0.14	0.07	0.08	7.0	0.00	1.77	1.25	0.05	73.7
AB - nCB	0.00	0.10	0.11	0.08	7.0	0.00	0.00	0.09	0.03	2.9
nAB - CB	0.11	0.13	0.13	0.05	10.1	1.91	0.00	0.00	0.00	45.8
nAB - nCB	0.08	0.04	0.21	0.06	9.4	1.06	0.00	0.00	0.00	25.4
AB - PB	0.09	0.00	0.00	0.08	4.1	0.00	3.23	2.61	0.18	144.5
AB - CBi	0.14	0.03	0.03	0.05	6.0	0.00	2.44	2.27	0.21	118.1
AB - CB (Ext.)	0.03	0.10	0.05	0.09	6.5	0.00	2.44	0.85	0.00	79.0
	N_2O (mg h^{-1})				**(mg)**	**NH_3 (mg h^{-1})**				**(mg)**
AB - CB	0.013	0.016	0.110	0.007	3.5	0.00	0.04	0.000	0.00	1.0
AB - nCB	0.025	0.015	0.114	0.059	5.1	0.00	0.04	0.000	0.00	1.0
nAB - CB	0.011	0.040	0.065	0.009	3.0	0.00	0.04	0.000	0.08	2.9
nAB - nCB	0.013	0.015	0.038	0.006	1.7	0.00	0.04	0.000	0.00	1.0
AB - PB	0.031	0.026	0.097	0.003	3.8	0.00	0.00	0.000	0.08	1.9
AB - CBi	0.028	0.032	0.116	0.003	4.3	0.00	0.00	0.000	0.08	1.9
AB - CB (Ext.)	0.011	0.039	0.013	0.004	1.6	0.00	0.00	0.000	0.08	1.9

**AB-CB: aerated bin and compostable bag; AB-nCB: aerated bin and non-compostable bag; nAB-CB: non-aerated bin and compostable bag; nAB-nCB: non-aerated bin and non-compostable bag; AB-PB: aerated bin and paper bag. Results are presented as average of three replicates. Standard deviation was very low and it is not presented.*

Table 4: Initial and final content of dry matter (% DM), organic matter (% OM) and dynamic respirometic index (DRI) determined for each sample.

Combination*	Initial			Final		
	DRI ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)	**% DM**	**% OM**	**DRI ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)**	**% DM**	**% OM**
AB - CB	5.5 ± 1.0	32 ± 2	86 ± 5	7.60 ± 0.03	25.6 ± 0.9	80.5 ± 0.1
AB - nCB				7.2 ± 0.3	28.1 ± 0.1	89 ± 9
nAB - CB				4.9 ± 0.3	32 ± 6	91 ± 3
nAB - nCB				6.3 ± 0.1	29.5 ± 0.3	93 ± 5
AB - PB				6.3 ± 0.4	34 ± 1	88.4 ± 0.4
AB - CB (Ext.)				5.00 ± 0.03	31 ± 2	88 ± 1

**AB-CB: aerated bin and compostable bag; AB-nCB: aerated bin and non-compostable bag; nAB-CB: non-aerated bin and compostable bag; nAB-nCB: non-aerated bin and non-compostable bag; AB-PB: aerated bin and paper bag. Results are presented as average of three replicates together with the standard deviation.*

Table 5: Impurities content in weight percentage found in different collection systems and the use of compostable bags (*Agència de Residus de Catalunya*, 2009).

		Impurities content (%)		
Compostable bag use	Not defined	12.06	6.07	11.63
	Mandatory	4.61	1.54	1.73
	Recommended	9.68	6.76	9.07
	Overall average	11.33	5.06	10.34
		Road Container	Door-to-door	Overall average
		Collection system		

Table 6: Economic balance assuming that no increase in the citizens' participation will occur in the OFMSW source-separated collection (studied case).

Impurities (weight, %)	OFMSW collected ($t\ year^{-1}$)		Difference ($t\ year^{-1}$)	Tax Refund decrease (€ $year^{-1}$)	Savings in the treatment of OFMSW (€ $year^{-1}$)	Final balance (€ $year^{-1}$)
	Non-Aerated system	Aerated system				
5.06	606.55	580.47	26.08	-1544.52*	1190.55**	-353.97

* 1544.52 € $year^{-1}$ = 26.08 t $year^{-1}$ x 33.5 € t^{-1} + 26.08 t $year^{-1}$ x 8.6 € t^{-1} x 1.5 (correction factor for a municipality of less then 5000 inhabitants) x Y (correction factor for impurities = -0.1 x 5.06 + 2.5 = 1.994)

** 1190.55 € $year^{-1}$ = 26.08 t $year^{-1}$ x 45.65 € t^{-1} (Table 2)

Table 7: Economic balance using a calculation basis of 606.55 t year^{-1} of generation of the OFMSW (case of a municipality of 4999 inhabitants). The expected increase in the citizens' participation in the source-separated collection of the OFMSW is calculated to compensate the decrease in the returned tax to the municipality.

Impurities (weight, %)	OFMSW collected (t year^{-1})			Difference non-aerated and aerated system (t year^{-1})	Tax Refund decrease (€ year^{-1})	Savings in the treatment of OFMSW (€ year^{-1})	Difference non-aerated system after and before increasing the participation (t year^{-1})	Savings in the landfill cost (€ year^{-1})	Final balance (€ year^{-1})
	Non-Aerated system (0.332 kg OFMSW inh^{-1} day^{-1})	Non-Aerated system (0.335 kg OFMSW inh^{-1} day^{-1})	Aerated system (after weight reduction)						
5.06	606.55	612.19(1)	585.8(2)	20.71	-1226.5(3)	945.4(4)	5.64	282.00(5)	0.90 (~0.0)

(1) Assuming and increase of participation of 0.93%

(2) Assuming a weight reduction of 4.3% with the aerated system

(3) 1226.5 € year^{-1} = 20.71 t year^{-1} x 33.5 € t^{-1} + 20.71 t year^{-1} x 8.6 € t^{-1} x 1.5 (correction factor for a municipality of less then 5000 inhabitants) x Y (correction factor for impurities = -0.1 x 5.06 + 2.5 = 1.994)

(4) 945.41 € year^{-1} = 20.71 t year^{-1} x 45.65 € t^{-1} (Table 2)

(5) 282.00 € year^{-1} =5.64 t year^{-1} x 50 € t^{-1} (40 € t^{-1} of average landfill cost plus a tax of 10 € t^{-1})

Legends to Figures

Figure 1: Image of the bins used in the study. Left: non-aerated bin (nAB); Right: aerated bin (AB).

Figure 2: Image of plastic bag (nCB) (left), paper bag (PB) (centre) and biodegradable bag (CB) (right) used in this study.

Figure 3: Cumulative reduction weight obtained daily for each combination of bin and bag. AB-CB: aerated bin and compostable bag; AB-nCB: aerated bin and non-compostable bag; nAB-CB: non-aerated bin and compostable bag; nAB-nCB: non-aerated bin and non-compostable bag; AB-PB: aerated bin and paper bag. Results are presented as average of three replicates jointly with the corresponding standard deviation.

Figure 4: Evolution of the temperatures measured inside each bin and around them (laboratory and environmental). AB-CB: aerated bin and compostable bag; AB-nCB: aerated bin and non-compostable bag; nAB-CB: non-aerated bin and compostable bag; nAB-nCB: non-aerated bin and non-compostable bag; AB-PB: aerated bin and paper bag. Results are presented as average of three replicates jointly with the corresponding standard deviation.

Fig. 1

Fig. 2

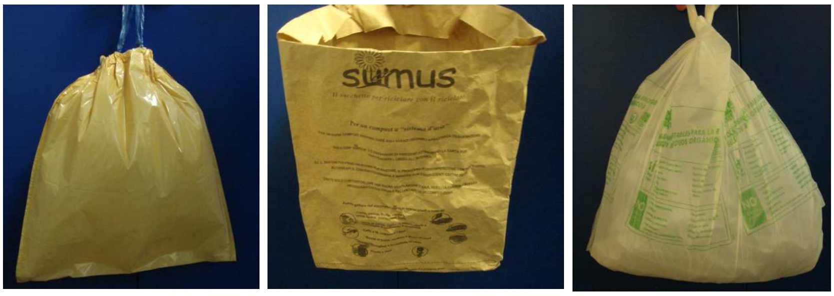
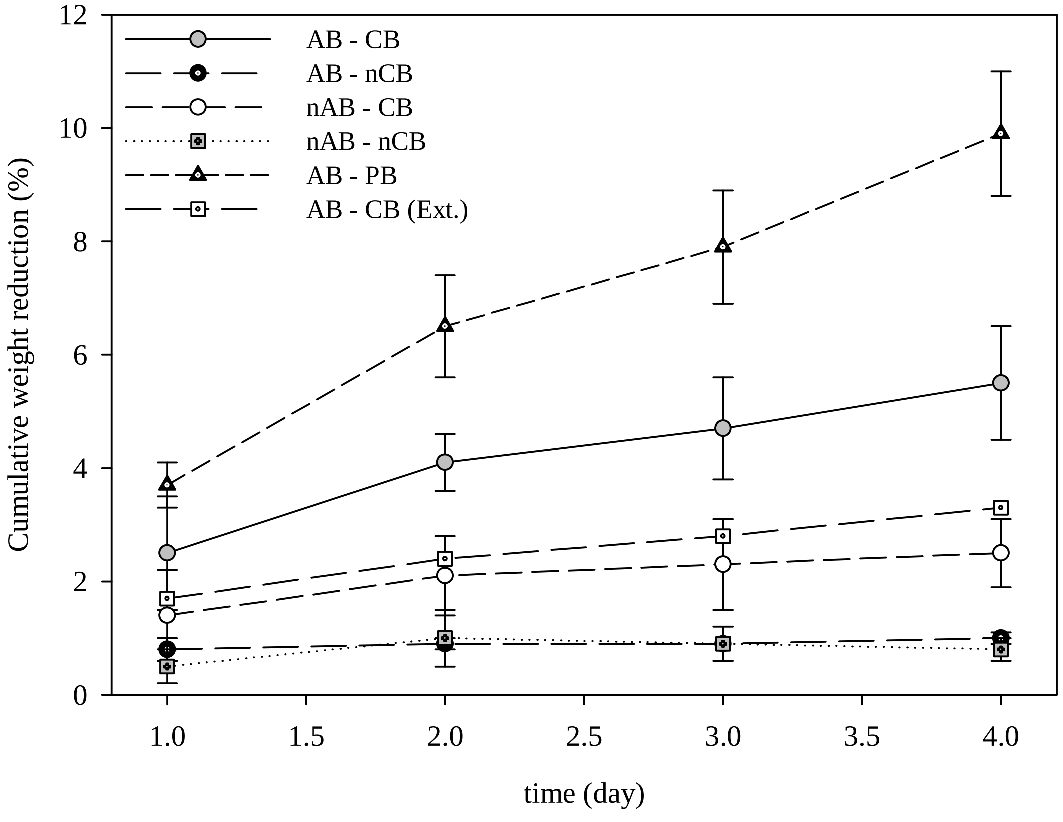
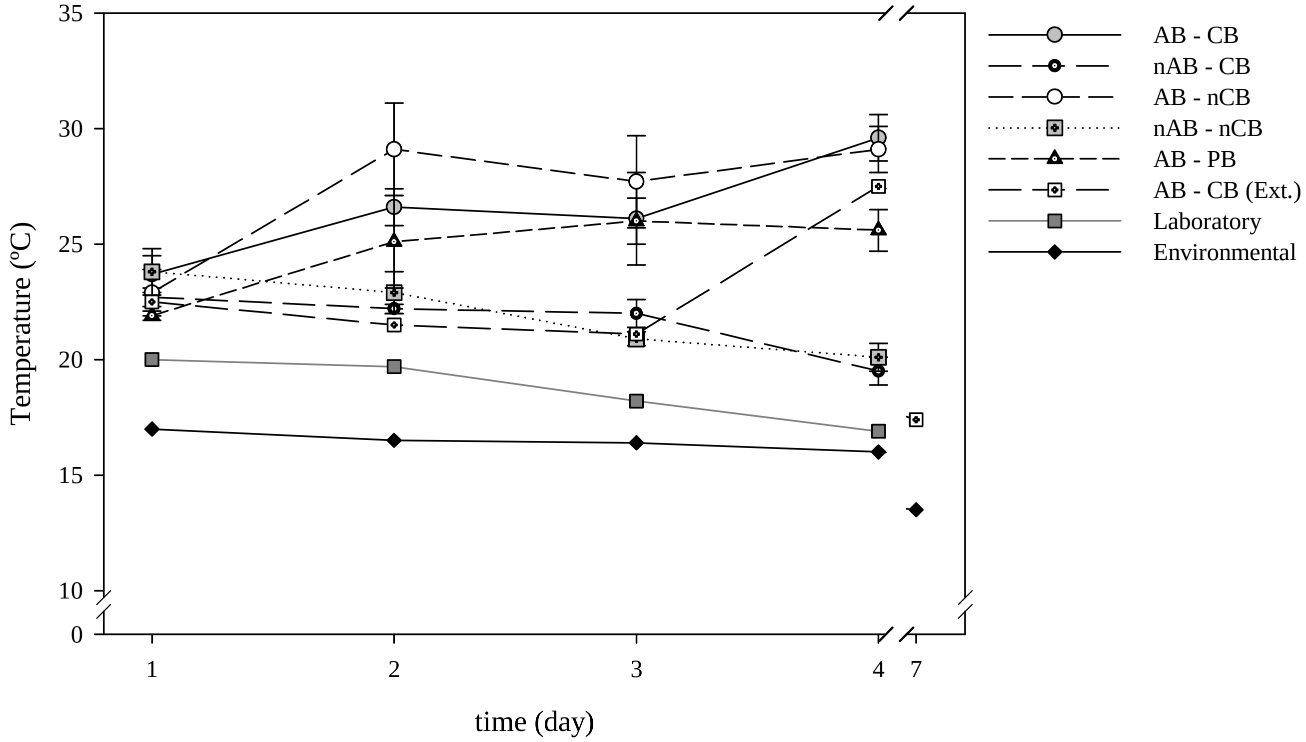


Fig.3



AB - CB
AB - nCB
nAB - CB
nAB - nCB
AB - PB
AB - CB (Ext.)
Cumulative weight reduction (%)
time (day)
0
2
4
6
8
10
12
1.0
1.5
2.0
2.5
3.0
3.5
4.0

Fig. 4


35
30
25
20
15
10
0
Temperature (ºC)
1
2
3
4
7
time (day)
AB - CB
nAB - CB
AB - nCB
nAB - nCB
AB - PB
AB - CB (Ext.)
Laboratory
Environmental