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# Comparison of compostable bags and aerated bins with conventional storage systems to collect the organic fraction of municipal solid waste from homes. A Catalonia case study

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ABSTRACT

The separation of biowaste at home is key to improving, facilitating and reducing the operational costs of the treatment of organic municipal waste. The conventional method of collecting such waste and separating it at home is usually done by using a sealed bin with a plastic bag. The use of modern compostable bags is starting to be implemented in some European countries. These compostable bags are made of biodegradable polymers, often from renewable sources. In addition to compostable bags, a new model of bin is also promoted that has a perforated surface that, together with the compostable bag, makes the so-called "aerated system". In this study, different combinations of home collection systems have been systematically studied in the laboratory and at home. The results obtained quantitatively demonstrate that the aerated bin and compostable bag system combination is effective at improving the collection of biowaste without significant gaseous emissions and preparing the organic waste for further composting as concluded 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 bin and bag combinations was carried in 100 homes in which more than 80% of the families participating preferred the aerated system.



## 1. Introduction

The organic fraction of municipal solid waste (OFMSW), or biowaste, is mainly composed of food rejects of vegetable or animal origin and green waste, in an amount that depends on the region considered (Eurostat, 2013). According to European recommendations and environmental considerations, these wastes need to be separately collected at home to be biologically treated through composting or anaerobic digestion to ensure the production of high quality compost, in accordance to new European regulations (European Union, 2008).

Catalonia, a well-developed region in the northeast of Spain is implementing an integrated system to collect source-separated OFMSW all over the territory. The last study about the municipal waste composition in Catalonia was carried out in 2004–2005 and showed that OFMSW, together with several other types of green waste, formed 36% (32% of kitchen waste and home green wastes and 4% of green wastes from municipalities, respectively) of the total weight of collected municipal wastes (Agència de Residus de Catalunya, 2006). In Spain, around 23 million tonnes of municipal solid waste (MSW) were collected in 2004. 2.3 million tonnes of this overall MSW stream were collected separately of which 262,221 tonnes were composted and 323,896 were anaerobically digested (Spanish Ministry of Environment, 2008). In Catalonia it is estimated that about 40% of MSW is collected by using a system that requires separation at home, mainly street bin or door-to-door systems. These values are steadily increasing in last years (Agència de Residus de Catalunya, 2006). Other waste streams are being incinerated and landfilled, options for waste treatment that have considerably decreased in last years. Specifically, 318,354 inhabitants (about 4% of the total population) have access to a door-to-door collection system, which means that 55,770 tonnes of biowaste could be collected through this system (Giró, 2006), being the rest of wastes collected by street bin systems. In recent years, the percentage of people participating in source separation systems has considerably increased, which is due to the tax incentives from the local government to improve the quality of the OFMSW, as explained later.

The management of OFMSW, including collection and processing, should be carried out as soon as possible and under conditions that minimise leachate and odours arising from the OFMSW owing to its high density, moisture and putrescibility. In 1993, Catalonia first started the separate collection of OFMSW, which has been

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gradually implemented all over the Catalan territory. Since then, the collection system has been continuously analysed and improved with specific actions such as the implementation of source-separate collection systems in all the municipalities of Catalonia, with information campaigns and delivering bags and bins for population to facilitate the separation jointly with a continuous monitoring of the OFMSW quality (Agència de Residus de Catalunya, 2012). Currently, different systems are used to collect biowaste: door-to-door and street containers being the most extended. In Europe, several collection systems have been implemented with different configurations, collection frequencies or source-separation schemes. The experience during these years has shown that the best collection systems in terms of valorisation and recycling of organic wastes imply the source-separation of the OFMSW. Among the systems proposed for source OFMSW separation, door-to-door systems have always shown better results in terms of recovery and quality of the material, which is typically collected for a biological treatment such as composting or anaerobic digestion (Giró, 2006; European Union, 2008; Huerta-Pujol et al., 2010). In any case, the collection systems start from the same point; the first step is separation at home, in which a bag in a bin with a total capacity of 10 L is commonly used. Normally, low-density polyethylene plastic bags have been used to collect OFMSW. Most of the plastics that arrive at composting plants as non-biodegradable materials and, consequently, impurities of the OFMSW, are the bags used to collect and dispose of OFMSW (Huerta-Pujol et al., 2010). Because polyethylene is not biodegradable, the presence of plastic 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 (CBs) made from corn or potato starch. The physical deterioration and biodegradation of these bags can be complete in just 6 days, under conditions similar to that of the composting process (Mohee and Unmar, 2006).

In recent years, a new system to separate organic waste at home has been introduced. This system, known as the "aerated system", comes from northern Europe. This system is based on the use of a perforated bin combined with CBs. By using this system the aeration of OFMSW is improved and the weight reduction of the waste through water evaporation is promoted. The continuous air exchange between the waste and the environment reduces unpleasant odours, which is one of the most common complaints about OFMSW separation at home (Agència de Residus de Catalunya, 2006). Moreover, the aerated system increases the mechanical resistance of the CB through drying of the bag surface.

The improvement of OFMSW quality through the general use of CBs could have a notable influence on municipal waste management, because treatment costs often depend on the percentage of impurities of the source-separated fractions. In general, taxes levied for waste treatment are used to optimise the municipal solid waste management system and improve the biological treatment of OFMSW to obtain biogas and/or high quality compost. For instance, in Catalonia, a specific tax is levied for any municipal waste that is finally disposed of in landfill or burned in an incineration plant (10 € $t^{-1}$ and 5 € $t^{-1}$, respectively) (Agència de Residus de Catalunya, 2006). The tax revenue raised is returned to compensate the municipalities for the cost of source-separated collections and for the maintenance of existing biowaste treatment plants and construction of new ones (by using biological processes such as composting, anaerobic digestion or a combination of both). The tax might cover all these costs but, obviously, this strongly depends on the level of implementation and participation in source separation, the public information campaigns and the perceptible benefits of the use of this tax in each municipality. Moreover, in Catalonia, part of this tax is returned to the municipalities and the amount is calculated according to the quality and quantity of the separated collection of OFMSW, so its value depends on each municipality characteristics and implication. Obviously, the final value of returned tax is dependent on positive participation by residents with the source-separated collection system, which could presumably increase with the use of the aerated system because results are more satisfactory for residents. In any case, the economic results of implementing this aerated system for a municipality depend on all the above-mentioned factors and require analysis.

Although LCA is not the main objective of this study, there is a number of literature reports on LCA of solid waste management and/or treatment processes (Blengini, 2008; Banar et al., 2009). In this framework all the data obtained on the storage of OFMSW at home allows a more complete LCA on the overall process of waste management.

The main goals of this work are: (i) to determine the efficiency of the different combinations to separate OFMSW at home (aerated or non-aerated bin and compostable or non-compostable bag) by using quantitative data on the characteristics of organic matter found in each system; (ii) to study the use of CBs in society and the effect on the impurities content of 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 a closed bin. In most cases, these bins are rectangular with a 10 L capacity and close tightly. Fig. 1 shows an image of a closed non-aerated bin (nAB) used at home together with the aerated bin (AB). Both bins are a similar shape and have the same total capacity.

### 2.2. Bags

Bags made from low-density polyethylene (hereon referred to as plastic), compostable biopolymers (Mater-Bi® product) and paper have been used in this study to collect OFMSW. Table 1 shows the main properties and general characteristics of these different bags. Currently, plastic or non-compostable bags (nCBs) are still the most widely used in Catalonia. CBs are made from synthetic biopolymers obtained from natural sources. The CBs used in this study were made from corn-starch. Paper bags (PBs) are also fully biodegradable but they have resistance problems when wet wastes are collected. Unlike plastic bags, which are made of fossil fuels, the raw materials of both CBs and PBs are obtained from crops. The images of the three types of bags are shown in Fig. 2.

**Fig. 1.** Image of the bins used in this study. Non-aerated bin (nAB; left); Aerated bin (AB; right).

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**Table 1**
Characteristics of plastic, compostable and paper bags to collect 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 – –: non-existent.

### *2.3. Experimental design in the laboratory*

All the possible combinations of the two bins and three bags available were studied. They were: (i) aerated bin with compostable bag (AB–CB), known as the aerated system; (ii) aerated bin with non-compostable bag (AB–nCB); (iii) non-aerated bin with compostable bag (nAB–CB); (iv) non-aerated bin with non-compostable bag (nAB–nCB). Triplicates of all these tests were carried out in the laboratory. An additional test sample of AB–CB was also placed outdoor with the aim to compare it with the inside experiments, as sometimes OFMSW bins are kept outside. Weather conditions in this case correspond to mild temperature (average temperature of 15 °C) and no rain during all the experiment and (v) to evaluate the use of PBs, one more experiment with the AB was included (AB–PB, in duplicate).

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

– Each day a volume of OFMSW equivalent to a quarter of the bin's total capacity was added to each bin (2.5 L, approximately 1.5 kg with a 65–70% of moisture content). The size of bins is standard (10 L) and they are normally designed to be completely filled twice a week for a typical family of 3–4 members. After 4 days the bins were full and the experiments were considered complete. This length was assumed for a typical family of three to four members that kept the bin indoor, in fact, it is relatively normal that organic wastes remain at home for some days, as the door-to-door collection systems are not designed to collect organic fraction every day, but to reserve days for the rest of streams. Only the bin placed outdoor was monitored for 7 days without the addition of further waste after day 4 to observe the evolution of organic matter in the absence of adding new waste (e.g. absence of the family). In this case, the objective was to test the behaviour of the bag and the bin in the outdoor conditions, but it is evident that this is a very particular situation that cannot be compared with the indoor systems.
– Every day the weight of raw waste added and the residual waste weight after 24 h was recorded and the weight loss for each bin combination calculated. The temperature of the bins was monitored at the centre of the solid material by using a temperature probe (Pt-100, Desin Instruments, Barcelona, Spain). The oxygen concentration was also measured by inserting an oxygen sensor (Lutron 5510, Lutron Co. Ltd., Taiwan) into the centre of the organic matrix, where the minimum concentration of interstitial oxygen was observed.
– The concentrations of four specific gases (methane, $N_2O$, ammonia and total volatile organic compounds (VOCs)) in each bin were recorded daily. To determine the gas concentration, each bin was isolated for 30 min in a cylindrical container with a total volume of 30 L. Afterwards, the gas around the bin was sampled in a Tedlar® bag and analysed by gas chromatography as explained and reported in Cadena et al. (2009a) and Colón et al. (2012).
– To complete the study, the material from each bin was analysed. Moisture, organic matter (OM) content and respirometric assays were undertaken. These three parameters were also determined in the initial sample of OFMSW.

### *2.4. Home experiments*

One hundred families, in four Catalan municipalities, were responsible for testing the four possible combinations of CB or nCB and AB or nAB with the organic waste that each family generated at home. The families were asked to test all combinations of bin: filling each bin several times, observing qualitatively leachate production and testing for unpleasant odours, as well as assessing the performance of the bags. Participating families were volunteers from a number of municipalities taking part in the study and were selected from four provinces in Catalonia (Barcelona, Tarragona, Lleida and Girona). 25 families living in apartments were selected from a large number of volunteers. These families were selected to include a cross-section of family types: married couples, married couples with one or two children and elderly people living alone. The experiment was carried out during an 8-week period by a team of four people who completed a questionnaire once a week after visiting each of the families participating in the study. Each combination of bag and bin was tested for 2 weeks, which included several cycles of collecting waste and disposal, using the same length than in the lab scale indoor experiments. Several qualitative aspects such as separation problems, resistance of bags, qualitative odour detection and general level of satisfaction were recorded after completion of each 2-week trial period.

### *2.5. Organic fraction of municipal solid waste*

The OFMSW used in the laboratory experiments was collected from the *Mancomunitat de la Plana* composting plant (Malla,


**Fig. 2.** Images of the plastic bags (nCB; left), paper bags (PB; centre) and compostable/biodegradable bags (CB; right) used in this study.

Barcelona, Spain) on the day the experiments started and originated from a door-to-door collection system. In the home experiments the OFMSW used was the organic waste produced by the families themselves. The waste average composition was similar to that of the OFMSW produced in other parts of Catalonia and Spain (Agència de Residus de Catalunya, 2006; Ruggieri et al., 2008). Specifically, the OFMSW presented the following general properties: moisture content of 62.3 ± 5.7%, organic matter of 70.6 ± 9.1% (in dry basis) and pH was 6.1 ± 0.2.

### 2.6. Analytical methods

Water content, dry matter (DM) and organic matter (OM) content were determined according to 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 by Ponsá et al. (2010), which was based on the methodology described by Adani et al. (2006). The DRI represents the average rate of oxygen uptake during a 24 h period of maximum biological activity observed during the respirometric assay (normally this rate is achieved 24–48 h 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 OM (or DM) per hour and measured in triplicate assays. A complete description of the dynamic respiration index methodology and its values can be found everywhere (Ponsá et al., 2010; Barrena et al., 2011).

### 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 conventional (nAB–nCB) system and considering the waste tax refund and the OFMSW treatment costs. 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 assuming an average value of 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 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 as a tax refund for the municipalities. This refund is calculated as a function of two criteria. Regarding the OFMSW treatment, the municipalities that deliver the source-separated OFMSW to a biological treatment facility receive 33.5 € per tonne of waste. Regarding the OFMSW separated collection, the biological treatment of OFMSW is encouraged by means of two correction factors that multiplies a standard value assigned to the collection of 1 t of 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 50,000, between 5000 and 50,000 and below 5000, respectively). The other correction factor ($Y$) is calculated according to the impurities contained in the OFMSW collected by using the equation: $Y = 2.5–0.1X$, where $X$ is the percentage of impurities (in total weight). Eq. (1) describes the tax refund given.

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

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 for the possible negative balance that the weight reduction from using the aerated system can produce (less weight collected means a reduction of the treatment cost and of the tax refund), an increase corresponding to 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 loss

The cumulative weight reduction of OFMSW obtained from the six bin combinations studied is shown in Fig. 3. The outdoor experiment was followed for 7 days, whereas the other ones were followed for 4 days, although a comparison between outside and inside experiments is not possible because of the differences of outdoor experiments, which should be considered independently. The results presented are the average values from the triplicate experiments except for the outdoor study, in which only a single experiment was monitored, and the results should be carefully interpreted. The results show that the AB–PB combination gave the highest weight reduction (Fig. 3). However, the PB was quickly discounted owing to its low resistance to moisture and its rapid deterioration, which makes PB not suitable for OFMSW collection at home. After discarding the PB because of the problems of mechanical resistance, the combination with the highest weight reduction was the indoor AB–CB system that achieved a total weight reduction of 5%. The nAB–CB combination gave an overall reduction of 2%. All experiments with nCBs had negligible weight reductions (<1%).

#### 3.1.2. Temperature monitoring

Fig. 4 shows the evolution of temperatures over time during the experiment. The results show that the laboratory temperature was approximately 20 °C for the first 2 days then decreased by 2 °C. The environmental temperature was more or less constant at 17 °C until the fourth day when it decreased considerably. The final temperature recorded was below 14 °C. It is evident that a complete comparison between inside and outside conditions needs a systematic study including several environmental conditions (temperatures wider range, rain, etc.). All the bin temperatures were within the range of 20–30 °C. In general, excluding the combinations with nABs, a clear relationship between the bin temperature evolution and the external temperature was not observed. However, a considerable change in the external temperature does affect the bin temperature. Although there are no previous experiences in literature, these results are similar to those obtained with home composting, which can be considered as the most similar situation than that of this study (Colón et al., 2010).

**Table 2**
Average cost for OFMSW treatment as a function of impurities in the 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 |

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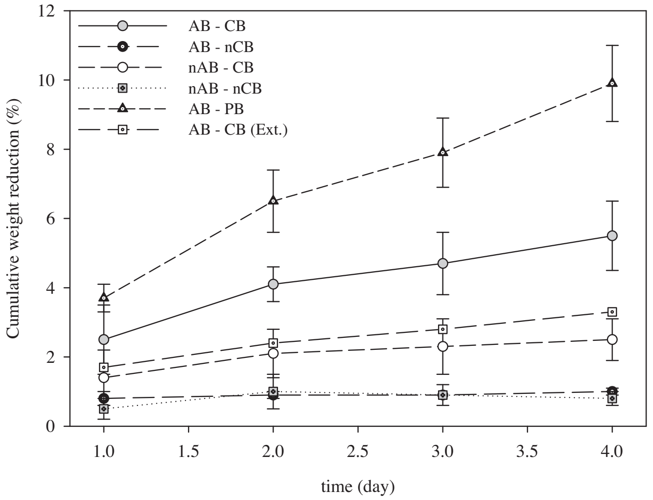


**Fig. 3.** Cumulative reduction weight obtained daily for each combination of bin and bag. AB–CB: aerated bin and compostable bag; AB–nCB: aerated bin and non-compostable bag; nAB–CB: non-aerated bin and compostable bag; nAB–nCB: non-aerated bin and non-compostable bag; AB–PB: aerated bin and paper bag; AB–CB (Ext.): aerated bin and compostable bag placed outdoor. The results presented are the average of three experiments and the corresponding standard deviations.

The temperature profiles showed that the indoor AB–CB system favoured composting conditions. It could be suggested that the composting process started in the bin owing to the high temperatures maintained during the experiment. After the start of the experiment, the temperature profiles of the aerated bins increased.

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

### 3.1.3. Gaseous emissions

Table 3 shows the emission profiles for methane, ammonia, $N_2O$ and VOCs for each experiment. In general, lower gaseous emissions were obtained when the values were compared with 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, which are normally different from that observed at lower scales (Cadena et al., 2009b; Colón et al., 2012). When emissions were recorded as zero, it implies that a similar concentration level of each pollutant was found in atmospheric air relative to the air surrounding the bin. In some cases, the emissions of the gases analysed were close to this threshold. Taking into account that the $NH_3$ values were always below 17 $ppm_v$ (the 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). In general, these emissions should be considered lower than those of small scale composting, such as home composting (Amlinger et al., 2008; Colón et al., 2010) and far beyond those observed at composting under full-scale conditions (Colón et al., 2012).

However, to the best of our knowledge, no literature values exist for studies of similar systems to enable a comparison with this study. As explained before, the only data that can be comparable are the gaseous emissions obtained during the biowaste composting at home or full scale (Amlinger et al., 2008; Colón et al., 2012), which gives numbers considerably lower than those presented in this work. Anyway, the data presented in this work could be useful to undertake an overall LCA on OFMSW management and treatment.

### 3.1.4. Respirometric indices, and dry matter and organic matter content

Initial values of DRI, DM and OM content of the OFMSW collected are shown in Table 4 together with the values obtained at the end of the experiments for each combination of collection system tested. In most cases, the DRI increased after the experiments began. This could mean that after the separation of waste at home the composting process begins soon after, which can be also related to the temperatures evolution (Fig. 4). This is typical during the composting process (Ruggieri et al., 2008).

The most significant increase of DRI was observed when CBs were used. In addition, the high DRI values obtained with CBs were statistically different from the initial DRI value. The low DRI for the

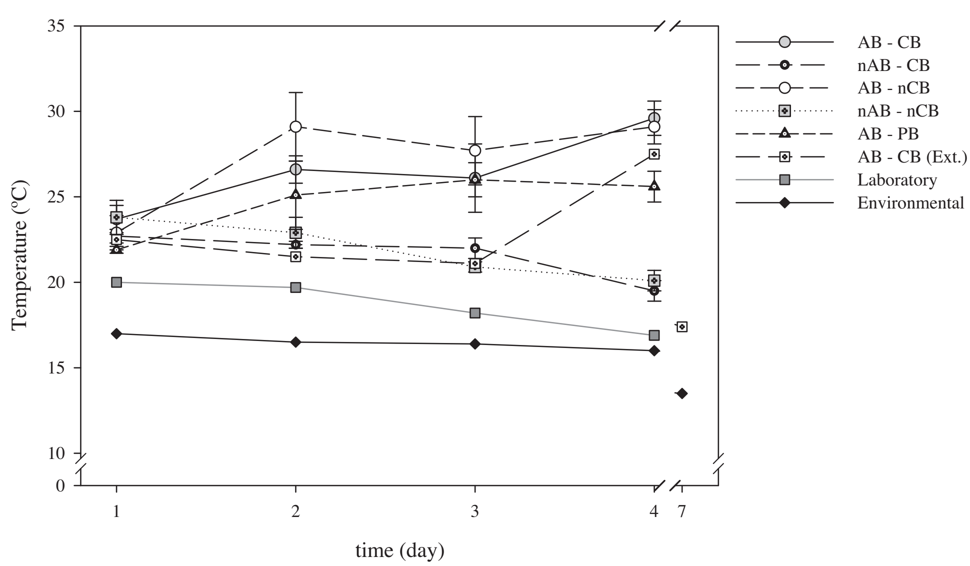


**Fig. 4.** Evolution of the temperatures measured inside each bin and around them (laboratory and environmental). AB–CB: aerated bin and compostable bag; AB–nCB: aerated bin and non-compostable bag; nAB–CB: non-aerated bin and compostable bag; nAB–nCB: non-aerated bin and non-compostable bag; AB–PB: aerated bin and paper bag. The results presented are the average of three experiments and the corresponding standard deviations.

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

| Combination[a] | Day 1 | Day 2 | Day 3 | Day 4 | Total (mg) | Day 1 | Day 2 | Day 3 | Day 4 | Total (mg) |
|---|---|---|---|---|---|---|---|---|---|---|
| | $CH_4$ (mg $h^{-1}$) | | | | | VOC (mg $h^{-1}$) | | | | |
| 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 $h^{-1}$) | | | | | $NH_3$ (mg $h^{-1}$) | | | | |
| 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 |

[a] 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. The results presented are the average of three experiments. Standard deviations were very low and are omitted for clarity.

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

| Combination[a] | 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 |

[a] 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. The results are presented the average of three experiments together with the standard deviation.

outdoor AB–CB system was probably a result of the final low temperature of this system but the exterior temperature effect on DRI is not known. Because no exterior experiments at higher environmental temperatures were undertaken, it can be hypothesised that the microbial populations responsible for the biodegradation needed a higher adaptation period when the temperature is considerably lower. It is important to note that the DRI is a single measure of biological activity at 37 °C (Ponsá et al., 2010). According to the DRI values obtained, the numbers can be classified under the category of highly biodegradable wastes, according to the ranges of DRI proposed by Barrena et al. (2011). However, it is clear that a complete composting process is necessary to reach a complete stabilization of organic matter (Ponsá et al., 2008).

The differences recorded in the DM and OM content for the samples at the beginning and at the end of the experiments were not statistically significant. This also happens with other processes such as the composting of biowaste at full scale (Ruggieri et al., 2008). In conclusion, the use of DRI is more appropriate (Ponsá et al., 2010). This is clear the most suitable parameter to consider in an overall LCA of the OFMSW (Colón et al., 2012).

Additionally, in other similar experiments (data not shown), the monitoring of the interstitial oxygen percentage of the waste over several days was followed. In general, a gradual decrease of the oxygen percentage was observed in all bins and bag combinations studied. After 2 days, the nABs registered an oxygen level close to 11%, whereas an oxygen content of 18% was measured in the ABs. From day 4, all oxygen levels recorded were below 5%. At the end of the experiment, the AB–CB combination showed that the aerated system maintained the highest oxygen levels although these values were still low (around 3%) relative to the surrounding air level (20.9%). In all other cases the oxygen levels recorded were below 1.5%, an indication of the high activity in the aerated system (Colón et al., 2012).

### 3.2. Home experiments

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

After the participating families had used each of the bin combinations they were asked to complete a survey about their experiences. The study achieved a 100% completion rate with all families participating in full. The results showed that, overall, the aerated AB–CB system was the most satisfactory combination. However, some problems with this system were noted. The most common problems were the fragility of the CB, insufficient bag size and difficulty in removing the bag from the bin to tie it up. Problems were reported in 10% of participating families. Although this study was undertaken during a relatively warm season (from April to June 2010 with daily temperatures 10–25 °C), some participants expressed concerns about how the aerated system might perform with higher ambient temperatures. Once the experiment was finished, a percentage of 85, 90, 80 and 80% of the families of each municipality studied were more satisfied with the aerated system. No reports of unpleasant odours, leachate or bag breaking were reported for the aerated system during the testing period.

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

| | Impurities content for each collection system (%) | | |
|---|---|---|---|
| | Road container | Door-to-door | Overall average |
| *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 |

Severe problems of leaching and the presence of condensates were reported with the nAB. The nAB appeared incompatible with the CB, which rapidly deteriorated because of excess moisture and wetting. In the nAB–nCB case, no bag deterioration was reported but the problem of leaching and condensation, resulting in odour problems, remained.

### 3.3. The use of compostable bags

One positive aspect of the use of CBs to carry out the source-separation of OFMSW is that their use is ethically aligned to an information campaign on the benefits of organic waste separation at home. In Catalonia, data obtained from the Catalan Waste Agency (Agència de Residus de Catalunya, 2009) confirmed greater public awareness of such issues. In summary, the mandatory use of CBs in door-to-door collection systems resulted in the lowest level of impurities (1.54%, Table 5), whereas when CB use was not mandatory the level of impurities was six times higher. Collection systems based on street containers also showed a significant reduction in impurities when the use of CBs was introduced (4.61% versus 12.06%, Table 5).

The treatment, in composting plants, of OFMSW with very low impurity levels is technologically simple, with low associated investment and operating costs because specialised equipment to remove and manage impurities may not be necessary. Moreover, the absence of impurities can help in implementing community composting schemes similar to those operating in some north-European countries (Pires et al., 2011).

Finally, some points regarding the presence of compostable polymers in compost must be noted. Klauss and Bidlingmaier (2004), in their study about compostable packaging materials, concluded that the biopolymer addition to organic waste did not affect the compost quality or its ability to be used for agricultural purposes. Moreover, Nakasaki et al. (2000) found that biodegradable polymers from natural sources can be used as ‘acid reservoirs’. Although the plastic is not acidic, it degrades and releases acid intermediates during the composting process, which can in part, counter some of the ammonia emissions generated during the composting process and reduced 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 in many countries to regulate the waste collection and treatment systems for municipal solid wastes. When organic matter from municipal waste 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 used. In Catalonia, part of the tax that is applied to each tonne of municipal solid waste that is disposed in a landfill or burned in an incineration plant (without having been source-separated) is returned to the Catalan municipalities in which the organic fraction is collected separately and treated in biological waste treatment plants. This system provides a very strong incentive for all municipalities to implement their own source-separated collection systems.

From an economic point of view, it is not clear if the use of the aerated system at home would be the most favourable for all municipalities. This study shows that the aerated system gave a higher weight reduction and resulted in a lower impurity percentage. These two facts combined imply that after replacing the conventional system (nAB–nCB) by the aerated system (AB–CB), the economic balance of the municipalities could change and must be analysed 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, because the temperature profile would be different and this affects the resulting weight reduction. On the other hand, the tax refund may increase because of the reduction in impurities (in the AB case) and the higher participation in the source-separation collection programmes as people show a higher level of satisfaction when using the AB–CB system. Therefore, the economic balance is not straightforward for each municipality.

For instance, assuming a total collection of OFMSW through the conventional system of 606.55 t year$^{-1}$ (an average weight for a small-size municipality without AB–CB) and assuming that after 3 days the weight reduction through the aerated system is around 4.3% (Fig. 3), the results of the economic balance after implementing the aerated system gives a slight deficit (−353.97 € year$^{-1}$, Table 6). To solve this problem it is necessary to increase citizens’ participation to compensate for the weight reduction resulting from the use of the aerated system produces because in the economic balance there is now a reduction in landfill or incineration costs (Table 7). In this case, the source-separated collected OFMSW should increase from 0.332 to 0.335 kg OFMSW inh$^{-1}$ day$^{-1}$, equivalent to 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, in which the optimal characteristics and benefits of the aerated system are explained. In fact, the aerated system is replacing other traditional systems used in Catalonia for the collection of OFMSW, although no official data are available. Nevertheless, additional research and monitoring of the AB–CB system should further confirm the benefits of its use.

**Table 6**
Economic balance assuming that no increase in citizens’ participation occurs with 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[a] | 1190.55[b] | −353.97 |

[a] 1544.52 € year$^{-1}$ = 26.08 t year$^{-1}$ × 33.5 € t$^{-1}$ + 26.08 t year$^{-1}$ × 8.6 € t$^{-1}$ × 1.5 (correction factor for a municipality of less than 5000 inhabitants) × *Y* (correction factor for impurities = 2.5–0.1 × 5.06 = 1.994).
[b] 1190.55 € year$^{-1}$ = 26.08 t year$^{-1}$ × 45.65 € t$^{-1}$ (Table 2).

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**Table 7**
Economic balance assuming 606.55 t year$^{-1}$ of OFMSW (typical for a municipality of 4999 inhabitants). The expected increase in the citizens' participation in the source-separated collection of OFMSW is calculated to compensate for the decrease in 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[a] | 585.8[b] | 20.71 | −1226.5[c] | 945.4[d] | 5.64 | 282.00[e] | 0.90 (~0.0) |

[a] Assuming and increase of participation of 0.93%.
[b] Assuming a weight reduction of 4.3% with the aerated system.
[c] 1226.5 € year$^{-1}$ = 20.71 t year$^{-1}$ × 33.5 € t$^{-1}$ + 20.71 t year$^{-1}$ × 8.6 € t$^{-1}$ × 1.5 (correction factor for a municipality of less than 5000 inhabitants) × *Y* (correction factor for impurities = 2.5–0.1 × 5.06 = 1.994).
[d] 945.41 € year$^{-1}$ = 20.71 t year$^{-1}$ × 45.65 € t$^{-1}$ (Table 2).
[e] 282.00 € year$^{-1}$ = 5.64 t year$^{-1}$ × 50 € t$^{-1}$ (40 € t$^{-1}$ of average landfill cost plus a tax of 10 € t$^{-1}$).

## 4. Conclusions

The aerated system (AB–CB) reduces the moisture content of the OFMSW owing to the breathability of the bags and the holes in the bin resulting in less weight of waste to be collected (5%), although the combination AB–PB also resulted in a high weight reduction.

Each combination of bin and bag studied resulted in a different percentage weight reduction of OFMSW. The highest weight reduction was obtained in the aerated system (AB–CB; 5% after 4 days), whereas the lowest weight reductions were measured with the non-aerated bin system with either CBs or nCBs, 1.0% and 0.8%, respectively.

Temperature, interstitial oxygen and DRI determined in the aerated system, along with gaseous emissions, demonstrated favourable conditions for biowaste storage at home. The data presented in this study could help towards a complete LCA considering the separation of organic wastes at home as the first step.

The home experiments resulted in a high level of citizen satisfaction with the AB–CB system. Typical negative issues related to the storage of organic matter at home (bad odours, leaching, flies) were not reported.

The estimation of the economic difference from complete implementation of an aerated system due to Catalan taxes on waste disposal showed a slightly negative result for the municipalities' tax refund. However, the increase in participation with source-separation of organic matter by citizens when they use the AB–CB system should easily compensate for this.

Further research is necessary to explore the results obtained with an outside storage of the OFMSW, as it is typical of other countries and the conclusions can be completely different.

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