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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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23 **Abstract**

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

41

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

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47 **1. Introduction**

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

53 Catalonia, a well-developed region in the north-east of Spain is implementing an  
54 overall system of source-separated collection of the OFMSW all over the Catalan territory.  
55 The last study about the municipal waste composition in Catalonia was carried out during the  
56 period 2004-2005 and showed that the OFMSW jointly with several typologies of green  
57 wastes were 36% (32% and 4%, respectively) of the total weigh of collected municipal  
58 wastes. More generally, in Spain about 23 millions of t of MSW were collected in 2004. 2.3  
59 millions of t of this overall MSW stream were separately collected and 262,221 t were  
60 composted and 323,896 were anaerobically digested (Spanish Ministry of Environment,  
61 2008). In Catalonia, it is estimated that about 40% of the MSW are collected with some  
62 system that implies separation at home, mainly street bin or door-to-door systems.  
63 Specifically, 318,354 inhabitants (about 4% of the total population) have access to a door-to-  
64 door collection system, which means that 55,770 t of biowaste could be collected with this  
65 system (Giró, 2006).

66 The management of the OFMSW (including collection and processing) should be  
67 carried out as soon as possible and under conditions that minimize the presence of leachate  
68 and odours due to the particular characteristics of the OFMSW such as a high density,  
69 moisture and putrescibility. In 1993, Catalonia started the first experiences with the separate  
70 collection of the OFMSW and it has been gradually implemented everywhere. Since then, the  
71 collection system has been continuously analyzed and improved. Currently, different systems

72 are used to collect biowaste: door-to-door and street containers are the most typical. In any  
73 case, both systems have the same starting point, the first step of separation at home, where a  
74 bag in a bin with a total capacity of 10 L is commonly used. Traditionally, low density  
75 polyethylene plastic bags (LD-PE) have been used to collect the OFMSW. Most of plastics  
76 that arrive at the composting plants as impurities correspond to the bags used to collect and  
77 dispose the OFMSW (Huerta-Pujol et al., 2010). As polyethylene is not biodegradable, the  
78 presence of these bags results in a problem during the composting process and makes the pre-  
79 and post-treatment more difficult (Körner et al., 2005). To avoid this problem, local  
80 administrations are now recommending the use of compostable bags that are composed of  
81 corn or potato starch. The physical deterioration and biodegradation of these bags can be  
82 completely achieved after six days (Mohee and Unmar, 2006).

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

91 The improvement of the OFMSW quality due to the generalized use of compostable  
92 bags could have a notable influence on municipal waste management, since its treatment cost  
93 often depends on the percentage of impurities of the source-separated fractions. In general, the  
94 waste taxes are used to optimize the municipal solid waste management and to improve the  
95 biological treatment of the OFMSW to obtain biogas and/or high quality compost. For  
96 instance, in Catalonia, a specific tax is applied to any municipal waste that is finally disposed

97 in a landfill or burned in an incineration plant (10 € t<sup>-1</sup> and 5 € t<sup>-1</sup>, respectively) without  
98 previous separate collection (*Agència de Residus de Catalunya*, 2006). The tax refund is  
99 returned to compensate the municipalities for the cost of source-separated collection and for  
100 the maintenance of existing plants and construction of new biowaste treatment plants (using  
101 biological process such as composting, anaerobic digestion or the combination of both).  
102 Specifically, in Catalonia, part of this tax is returned to the municipalities and it is calculated  
103 according to the quality and quantity of the separated collection of the OFMSW. Obviously,  
104 the final value of returned money is also highly dependent on the people's participation in the  
105 separation of source-separated collection system, which could presumably increase with the  
106 use of the aerated system since they results are more satisfactory for the population. In any  
107 case, the economic results of implementing this aerated system for a municipality depend on  
108 all the abovementioned factors and need a deep analysis.

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

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

121

## 122 **2. Materials and Methods**

### 123 *2.1. Bins*

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

128

### 129 *2.2. Bags*

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

141

### 142 *2.3. Experimental design at laboratory*

143 All the possible combinations among the bins and bags described were studied, i.e. (i)  
144 aerated bin with compostable bag (AB-CB), from now on the aerated system, (ii) aerated bin  
145 with non-compostable bag (AB-nCB), (iii) non-aerated bin with compostable bag (nAB-CB)  
146 and (iv) non-aerated bin with non-compostable bag (nAB-nCB). Triplicates of all these tests

147 were carried out in the laboratory. One more sample of the combination (i) was also placed  
148 outdoors, since sometimes the bin of the OFMSW is placed outside. To study the use of the  
149 paper bag (PB), one more assay was included (in duplicate) only with the aerated bin (AB-  
150 PB).

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

152 - A quarter part of the total capacity of each bin was daily filled with the OFMSW. After the  
153 fourth day the bins were totally filled. Therefore, it was considered that the experiment was  
154 finished. Only the bin placed outdoors was monitored until the seventh day without adding  
155 more waste.

156 - Every day the raw waste added and the weight value after a 24-h period were measured to  
157 know the weight loss of each combination. Temperature was also monitored. This measure  
158 was determined in the centre of the solid material using a temperature probe (Pt-100, Desin  
159 Instruments, Barcelona, Spain). Additionally, the oxygen concentration was also measured  
160 inserting an oxygen sensor (Lutron 5510, Lutron Co. Ltd., Taiwan) in the centre of the  
161 organic matrix, where the minimal concentration of interstitial oxygen was observed.

162 - The concentrations of four specific gases (methane, N<sub>2</sub>O, ammonia and total Volatile  
163 Organic Compounds (VOCs)) were daily determined in each bin. To determine the gas  
164 concentration, each bin was isolated during 30 minutes in a cylindrical container of a total  
165 volume of 30 L. Afterwards, the gas around the bin was sampled in a Tedlar® bag and  
166 analyzed by gas chromatography as explained and reported in Cadena et al. (2009a).

167 - To finish the study, the material obtained in each experimental combination was analyzed.  
168 Moisture, organic matter content and respirometric assays were undertaken. These three  
169 parameters were also determined in the initial sample of the OFMSW.

170

171 *2.4. Home experiments*



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

188

#### 189 *2.5. Organic Fraction of Municipal Solid Waste (OFMSW)*

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

194

#### 195 *2.6. Analytical Methods*

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

199 To obtain the Dynamic Respirometric Index (DRI), microbial respiration was  
200 measured as O<sub>2</sub> consumption in a dynamic respirometer built and started-up by Ponsá et al.  
201 (2010), which was based on the methodology described by Adani et al. (2006). The DRI  
202 represents the average oxygen uptake rate during the 24-h period of maximum biological  
203 activity observed during the respirometric assay (normally, it is achieved between 24 or 48  
204 hours after starting the test) and it reports the material stability degree (Adani et al., 2004;  
205 Ponsá et al., 2010). It is expressed in mg of O<sub>2</sub> consumed per g of organic matter (or dry  
206 matter) per hour and measured in triplicate assays.

207 As previously commented, the monitored gases (methane, N<sub>2</sub>O, ammonia and VOCs)  
208 were analyzed following the methods developed and started-up by Cadena et al. (2009a).

209

## 210 *2.7. Economic balance*

211 The economic balance was estimated by relating the experimental difference found  
212 between the weights of the OFMSW collected per year through the aerated (AB-CB) and the  
213 traditional system (nAB-nCB) and considering the wastes tax refund and the OFMSW  
214 treatment cost. The balance presented in this work shows the results for a municipality of  
215 4999 inhabitants (small-size municipality) with a door-to-door collection system, as example,  
216 and assuming an average value of the OFMSW collected of 0.332 kg inh<sup>-1</sup> day<sup>-1</sup>. The data and  
217 local prices necessary to calculate the economic balance were provided by the Catalan Waste  
218 Agency (*Agència de Residus de Catalunya*, 2009; 2010).

219 In the year 2010, part of the tax of MSW disposition in landfills or incineration plants  
220 was assigned to the source-separated OFMSW treatment and to improve the selective

221 collection of this fraction, both points as tax refund for the municipalities. This refund is  
222 calculated as a function of two points. Regarding the OFMSW treatment, the municipalities  
223 that deliver the source-separated OFMSW in a biological treatment facility receive 33.5 € per  
224 tonne of waste. Regarding the OFMSW separated collection, the quality of the OFMSW  
225 treated with biological treatments is encouraged by means of two correction factors that  
226 multiplies a standard value assigned to the collection of one t of the OFMSW (8.6 € t<sup>-1</sup>). One  
227 factor (Z) depends on the number of inhabitants (1, 1.28 or 1.5 for a number of inhabitants  
228 over 50000, between 5000 and 50000 and below 5000, respectively). The other correction  
229 factor (Y) is calculated according to the impurities content of the OFMSW collected using the  
230 equation:  $Y = -0.1X + 2.5$ , where X is the percentage of impurities (in total weight). In general,  
231 the equation that describes the tax refund is the next (equation 1):

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

233 (Equation 1)

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

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

244

### 245 **3. Results and discussion**

246 *3.1. Laboratory experiments*

247 *3.1.1. Weight losses*

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

262

263 *3.1.2. Temperature monitoring*

264         Figure 4 shows the evolution of temperatures during the experimental monitored  
265 period. In order to determine the influence of the external conditions on the bin temperature,  
266 the environmental and laboratory temperatures were also recorded. As can be observed, the  
267 laboratory temperature was around 20 °C during the first two days; afterwards it decreased 2  
268 °C. The environmental temperature was more or less constant at 17 °C until the fourth day of  
269 study. From this day, the environmental temperature decreased considerably. The last  
270 temperature value recorded was below 14 °C.

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

276 The temperature profiles showed that the indoor aerated system favoured the  
277 composting conditions. It could be suggested that the composting process started by itself in  
278 the bin due to the high temperatures maintained during the experiment. The results obtained  
279 for the outdoor aerated system showed a similar maximum temperature than the one of the  
280 indoor system, although its evolution was different from the rest of aerated bin experiments.  
281 After starting, the temperature profiles of the aerated bins increased. Contrarily, in the outdoor  
282 aerated system the temperature only increased from the third day. It can be hypothesized that  
283 this was due to the difference between the laboratory and the environmental temperatures.  
284 From the fourth day, the temperature of the outdoor experiment decreased approximately 10  
285 °C. The material compaction and the environmental temperature decrease were probably the  
286 causes for this decrease.

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

291

### 292 *3.1.3. Gaseous emissions*

293 Table 3 shows the emissions profiles of the gases considered (methane, ammonia, N<sub>2</sub>O  
294 and VOCs) for each experiment. The gaseous emissions are expressed as mg of gas  
295 compound emitted per hour and in form of cumulative emissions for each gas. In general,

296 lower gaseous emissions were obtained when the values were compared to the industrial and  
297 home composting processes, although this fact can be a consequence of the different ranges of  
298 temperature and pH observed at full-scale (Cadena et al., 2009b; Colón et al., 2012). When  
299 emissions are equal to zero, it implies that a similar concentration level of each pollutant was  
300 found in atmospheric air when compared to the bin surrounding air. In some cases, the  
301 emissions of the gases analyzed were close to this threshold. In any case, taking into account  
302 that the NH<sub>3</sub> measures were always below 17 ppm<sub>v</sub> (odour threshold), the best combination  
303 should be considered as a function of the environmental impact of CH<sub>4</sub> and N<sub>2</sub>O as CO<sub>2</sub>  
304 equivalents: 25 kg<sub>eq</sub>CO<sub>2</sub> and 296 kg<sub>eq</sub>CO<sub>2</sub>, respectively (IPCC, 2006). Adding the CO<sub>2</sub>  
305 equivalents of CH<sub>4</sub> and N<sub>2</sub>O for each combination the results showed that no significant  
306 differences were observed (data not shown).

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

310

#### 311 *3.1.4. Respirometric Indices, dry matter and organic matter content*

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

319         The most significant increase of DRI was observed using compostable bags, except for  
320 the outdoor aerated system, which produced the lowest value. In addition, high DRI values

321 obtained with the use of compostable bags were only statistically different from the initial  
322 DRI value. The low DRI of the outdoor aerated system was probably due to the final low  
323 temperature found in this system. In fact, the exterior temperature effect on the DRI is not  
324 known. Since no exterior experiments at higher environmental temperatures were undertaken,  
325 it can be hypothesized that the microbial populations responsible for the biodegradation  
326 needed a higher adaptation period when the temperature is considerably low as it is important  
327 to note that the DRI is a single measure of the biological activity at 37°C (Ponsá et al., 2010).

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

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

342

### 343 *3.2. Home experiments*

344 The qualitative monitoring of the home experiments was basically focused on practical  
345 aspects such as the bin location at home, the characteristics of the wastes collected, storage

346 time at home, satisfaction level (odours, bag resistance, etc.), personal opinions about the best  
347 system and why, among others.

348         After the experience with the several combinations of the collection systems tested,  
349 the same survey was sent to all the project participants. All the families participated in the full  
350 experiment and none of them drop out. The general results showed that the aerated system  
351 was the most satisfactory combination. However, some incidences with this system were also  
352 commented. The most frequent incidences reported were the apparent fragility of the  
353 compostable bag, an insufficient bag size and the difficulty to remove the bag from the bin  
354 and to tie it up. Some participants expressed doubts about the behaviour of the aerated system  
355 with higher ambient temperatures that were not reached during this set of experiments,  
356 although the study was undertaken in a relatively warm season (from April to June of 2010  
357 when the recorded temperatures were within 10 to 25 °C). At the end of the experience, 85%,  
358 90%, 80% and 80% of the people of each municipality preferred the aerated system. The  
359 percentage of incidences using this system (mainly related to the apparent fragility of  
360 compostable bags and an insufficient bag size) were around 10% of the participating people.  
361 No incidences were reported on the detection of unpleasant odours, leachate or bag breaking  
362 in the case of the aerated system.

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

368

369 *3.3. The use of compostable bags*



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

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

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

392

393 *3.4. Economic viability of the aerated system for municipalities*

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

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

415 For instance, assuming a total collection of the OFMSW with the traditional system of  
416 606.55 t year<sup>-1</sup> as calculation basis (it corresponds to a case of a small-size municipality) and  
417 assuming that after 3 days the weight reduction through the aerated system is around 4.3%  
418 (Figure 3), the results of the economic balance after implementing the aerated system

419 confirmed a slightly negative difference (-353.97 €year<sup>-1</sup>, Table 6). To solve this problem it is  
420 necessary an increase of the citizens' participation to compensate this weight reduction that  
421 the aerated system produces because it appears a new parameter in the economic balance,  
422 which is the reduction of landfill or incineration cost (Table 7). Specifically, for the case  
423 analyzed the source-separated collected OFMSW should increase only from 0.332 to 0.335 kg  
424 OFMSW inh<sup>-1</sup> day<sup>-1</sup> i.e., 0.93%. According to the level of satisfaction associated to the  
425 aerated system, it is reasonable to predict that the participation will increase with this system  
426 after an informative campaign, where the optimal characteristics and benefits of the aerated  
427 system are detailed. In fact, the aerated system is replacing other traditional systems used in  
428 Catalonia used for the collection of OFMSW although, no official data are available.  
429 Nevertheless, further research and implementation monitoring of this system should confirm  
430 these points.

431

#### 432 **4. Conclusions**

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

436 Different weight reductions were detected in all the combinations of bins and bags  
437 studied. The highest weight reduction was obtained in the aerated system (5% after four  
438 days). On the contrary, the lowest weight reductions were measured in non-aerated bins: 1.0  
439 % and 0.8% in combination with compostable and non-compostable bags, respectively.

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

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

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

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

453

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463

464

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## Tables

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

	<b>Plastic bags</b>	<b>Compostable bags</b>	<b>Paper bags</b>
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<sup>-1</sup>) (*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 <sup>-1</sup> )	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 <sub>4</sub> (mg h <sup>-1</sup> )				(mg)	VOC (mg h <sup>-1</sup> )				(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 <sub>2</sub> O (mg h <sup>-1</sup> )				(mg)	NH <sub>3</sub> (mg h <sup>-1</sup> )				(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 respirometric index (DRI) determined for each sample.

Combination*	Initial			Final		
	DRI (mg O <sub>2</sub> g OM <sup>-1</sup> h <sup>-1</sup> )	% DM	% OM	DRI (mg O <sub>2</sub> g OM <sup>-1</sup> h <sup>-1</sup> )	% DM	% OM
AB - CB				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	5.5 ± 1.0	32 ± 2	86 ± 5	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 <sup>-1</sup> )		Difference (t year <sup>-1</sup> )	Tax Refund decrease (€ year <sup>-1</sup> )	Savings in the treatment of OFMSW (€ year <sup>-1</sup> )	Final balance (€ year <sup>-1</sup> )
	Non-Aerated system	Aerated system				
5.06	606.55	580.47	26.08	-1544.52*	1190.55**	-353.97

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

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

**Table 7:** Economic balance using a calculation basis of 606.55 t year<sup>-1</sup> 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 <sup>-1</sup> )			Difference non-aerated and aerated system (t year <sup>-1</sup> )	Tax Refund decrease (€ year <sup>-1</sup> )	Savings in the treatment of OFMSW (€ year <sup>-1</sup> )	Difference non-aerated system after and before increasing the participation (t year <sup>-1</sup> )	Savings in the landfill cost (€ year <sup>-1</sup> )	Final balance (€ year <sup>-1</sup> )
	Non-Aerated system (0.332 kg OFMSW inh <sup>-1</sup> day <sup>-1</sup> )	Non-Aerated system (0.335 kg OFMSW inh <sup>-1</sup> day <sup>-1</sup> )	Aerated system (after weight reduction) <sup>(2)</sup>						
5.06	606.55	612.19 <sup>(1)</sup>	585.8 <sup>(2)</sup>	20.71	-1226.5 <sup>(3)</sup>	945.4 <sup>(4)</sup>	5.64	282.00 <sup>(5)</sup>	0.90 (~0.0)

<sup>(1)</sup> Assuming an increase of participation of 0.93%

<sup>(2)</sup> Assuming a weight reduction of 4.3% with the aerated system

<sup>(3)</sup> 1226.5 € year<sup>-1</sup> = 20.71 t year<sup>-1</sup> x 33.5 € t<sup>-1</sup> + 20.71 t year<sup>-1</sup> x 8.6 € t<sup>-1</sup> x 1.5 (correction factor for a municipality of less than 5000 inhabitants) x Y (correction factor for impurities = -0.1 x 5.06 + 2.5 = 1.994)

<sup>(4)</sup> 945.41 € year<sup>-1</sup> = 20.71 t year<sup>-1</sup> x 45.65 € t<sup>-1</sup> (Table 2)

<sup>(5)</sup> 282.00 € year<sup>-1</sup> = 5.64 t year<sup>-1</sup> x 50 € t<sup>-1</sup> (40 € t<sup>-1</sup> of average landfill cost plus a tax of 10 € t<sup>-1</sup>)

## 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

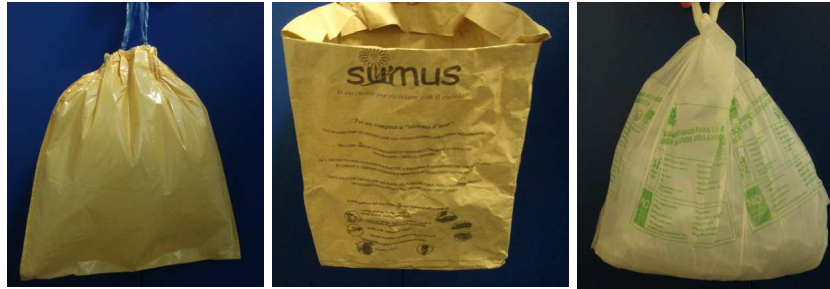


Fig.3

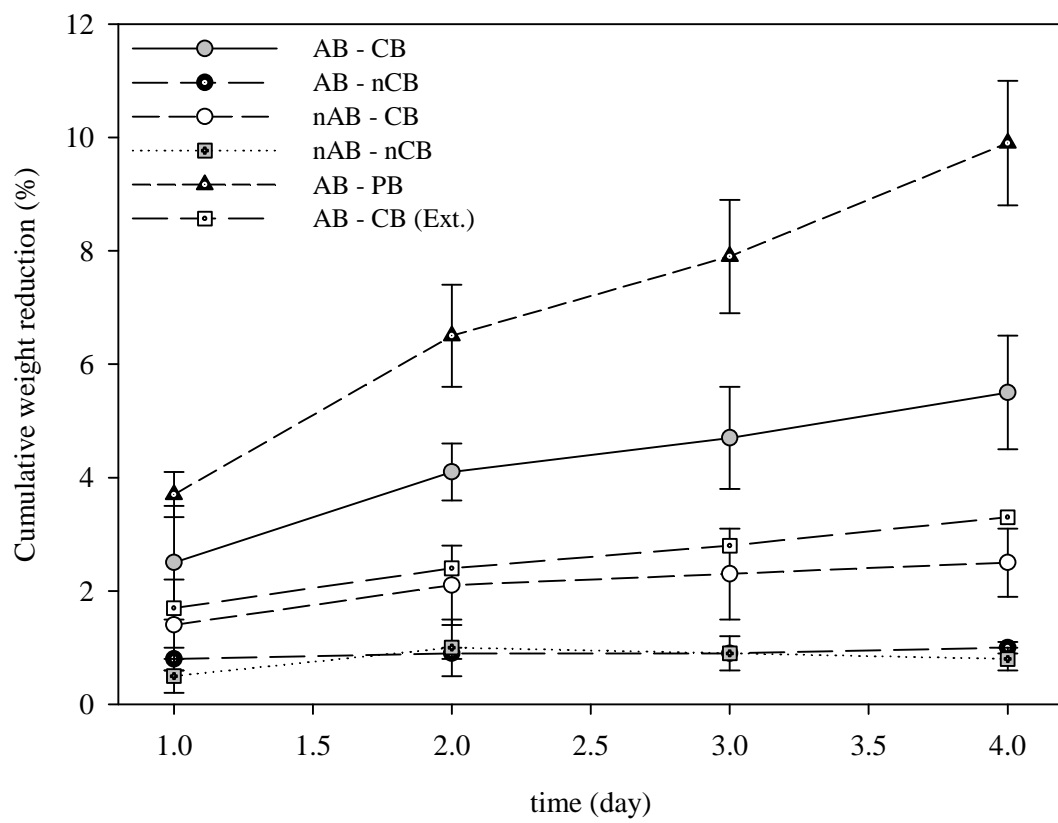


Fig. 4

