

Possibilities of composting disposable diapers with municipal solid wastes

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Abstract

The possibilities for the management of disposable diapers in municipal solid waste have been studied. An in-depth revision of literature about generation, composition and current treatment options for disposable diapers showed that the situation for these wastes is not clearly defined in developed recycling societies. As a promising technology, composting of diapers with source-separated organic fraction of municipal solid waste (OFMSW) was studied at full scale to understand the process performance and the characteristics of the compost obtained when compared with that of composting OFMSW without diapers. The experiments demonstrated that the composting process presented similar trends in terms of evolution of routine parameters (temperature, oxygen content, moisture and organic matter content) and biological activity (measured as respiration index). In relation to the quality of both composts, it can be concluded that both materials were identical in terms of stability, maturity and phytotoxicity and showed no presence of pathogenic micro-organisms. However, compost coming from OFMSW with a 3% of disposable diapers presented a slightly higher level of zinc, which can prevent the use of large amounts of diapers mixed with OFMSW.

Keywords

composting, diapers, environmental impact, municipal solid wastes, waste collection

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Introduction

In recent years the continuous growth in waste generation has become one of the main environmental problems that modern societies have to face. The increasing environmental awareness in society along with an increasing difficulty in locating waste facilities such as waste incinerators and landfills (Alçada-Almeida et al., 2009), has lead public administrations to search for alternative waste management solutions, such as composting or recycling.

In particular, in Europe, the recent Directive 2008/98/EC of 19 November 2008 on Waste establishes the following waste hierarchy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, such as energy recovery; and (e) disposal' (art. 4). Additionally, Directive 1999/31/EC of 31 April on the landfill of waste sets up significant restrictions on the disposal of biodegradable materials in landfills. According to this Directive, by 2016 the biodegradable municipal waste going to landfills must be reduced to 35% of the total amount (by weight) of biodegradable municipal waste produced in 1995.

Diaper wastes have a significant proportion of organic materials in their composition, but their final destination in most of the countries is landfill or incineration. In municipalities where high levels of separate waste collection are reached, disposable diapers account for a significant part of the refuse fraction and constitute one of the main difficulties in increasing the recycling levels.

As first objective and based on a literature review, the next section describes the main impacts of disposable diapers and the following section details possible alternative treatments. As a second objective, it experimentally analyses the

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compostability of disposable diapers mixed with the organic fraction of municipal solid waste (OFMSW), as a possible alternative treatment to landfill or incineration. Finally, some conclusions are presented.

Environmental impacts of disposable diapers

Composition of disposable diapers

The composition of disposable diapers is very diverse in terms of the materials used (Table 1). Additionally, when considering their treatment as waste, in used disposable diapers the presence of solid and liquid excreta also has to be considered. In fact, they represent the two most significant fractions in weight (Table 2). According to Campbell and McIntosh (1998), the generation of solid and liquid excreta between the age of 0 and 30 months ranges from 0.448 to 0.601 kg day⁻¹ per child (Table 3).

The average weight of a clean disposable diaper is 41 g (EDANA, 2007). The average weight for a used disposable diaper is 212 g, according to experimental data based on the average weight of 610 diapers collected in municipalities of Mancomunitat La Plana (Barcelona, Spain) between 18 and 24 February 2008. Furthermore, the organic part of diapers,

Table 1. Average baby diaper composition in 2006

Material	Weight percentage (%)
Cellulose pulp	35
Superabsorbent polymer (SAP)	33
Polypropylene	17
Polystyrene	6
Adhesives	4
Other	4
Elastics	1

Source: EDANA (2007).

Table 2. Average composition of used disposable baby diapers

Material	Weight (g)	Weight percentage (%)
Non organic materials (SAP, polypropylene, polystyrene, adhesives, elastics, other)	0.027	12.74
Cellulose pulp	0.014	6.60
Faeces	0.010	4.72
Urine	0.161	75.94
Total organic without urine	0.024	11.37
Total organic with urine	0.185	87.43

Source: own elaboration based on EDANA (2007), Campbell and MacIntosh (1998) and empirical data from 610 baby diapers produced in Mancomunitat La Plana (Barcelona, Spain).

considering only cellulose and solid excreta, accounts for 11.4% of their weight. When urine is also included in the organic part, this increases to 87.4% of their weight (Table 2).

On the other hand, several aspects have to be considered in relation to the presence of superabsorbent polymers (SAP) in diapers. SAP are polymers with high molecular weight presenting the ability to absorb and retain high quantities of liquid in comparison with their own weight. In contact with urine, SAP take the form of a gelatinous mixture known as hydrogel. Thus, although urine is an organic substance, in terms of the visual impact during the composting process, it could be considered an impurity since the high adherence of hydrated SAP to organic materials would make it very difficult to separate it in composting plants. However, according to Cook et al. (1997), the composting process degrades the polymer cross-linkages responsible for the gel formation, urine is released and it can be degraded normally. On the contrary, the SAP molecules are only degraded by 8% during a 100 days composting period, although residual polymers continue to degrade (at a rate of 0.007% day⁻¹), which suggests that they will eventually degrade completely. However, given this long degradation time estimate for SAP, it must be pointed out that some harmful effects can appear for human and other environments, as previously reported (Friedman, 2003; Andersen, 2005; Weston et al., 2009), although new materials used for SAP fabrication claim not to be toxic (Demitri et al., 2008; Kosemund et al., 2009). Nevertheless, regarding the composting process, only non-biodegradable molecules should be considered as impurities. Once released, urine initially retained in SAP would be composted with the organic matter present in the mixture.

Generation of disposable diapers: collection and treatment systems

The generation of waste from disposable diapers has been estimated based on empirical data (sample of 610 used diapers, see above) and bibliographical data on the percentage of children using diapers at different ages (Environment Agency, 2004). The main results are shown in Table 4.

Table 3. Average excreta production per child

Age (months)	Urine mass rate (kg day ⁻¹)	Faeces mass rate (kg day ⁻¹)	Total mass rate (kg day ⁻¹)
0–3	0.42	0.028	0.448
3–6	0.42	0.031	0.451
6–12	0.47	0.031	0.501
12–24	0.58	0.031	0.611
24–30	0.57	0.031	0.601

Source: Campbell and McIntosh (1998).

Table 4. Average diaper production per child

Age (months)	Children wearing diapers (%)	No. changes day ⁻¹	Average diaper weight (kg)	Diapers weight per child (kg year ⁻¹)
Up to 6	100	7	0.21	536.55
6–12	95.7	7		513.48
12–18	82.8	5		317.33
18–24	45.6	5		174.76
24–30	17.6	5		67.45
30–36	4.8	5		18.40

Source: own elaboration based on US Environment Agency (2004) and empirical data from 610 baby diapers produced in Mancomunitat La Plana (Barcelona, Spain).

The estimated generation of waste from disposable diapers in Europe in 2007 (considering births in 2005–2007) was 4 278 461 tonnes, which is 1.66% of total municipal waste generation, and around 3% of the organic waste fraction present in the municipal solid waste stream. In most European countries, diapers are collected together with the refuse waste and have the same destination. According to Eurostat (2009), in 2006, 61% of municipal solid waste went to landfills or waste incinerators, whereas 39% had other destinations, such as recycling or composting.

Environmental impact: The main environmental impacts of disposable diapers occur during the manufacturing process and during their treatment in landfills or incinerators. Impacts occurred during commercialization, transport and use are considered less important (Aumônier and Collins, 2005). A brief description of the main impacts is presented below.

1. During the manufacturing process.

- The main component of diapers is cellulose pulp (35% in baby diapers, Table 1), which is mainly obtained from coniferous woods. Associated environmental impacts are deforestation (in case of cellulose pulp obtained from natural forests) or loss of soil quality and loss of biodiversity (in case of cellulose from plantations of fast-growing species). Manufacturing of pulp involves the extensive use of chlorine and alkalis which often ends up in an effluent and results in the synthesis of other potentially harmful substances like dioxins and furans (Lehrburguer et al., 1991).
- Super absorbent polymers account for 33% of the diapers weight (EDANA 2007). SAP is formed by sodium polyacrylate crystals. The only references found on the fate of superabsorbent polymers in soil after composting (Stegmann et al., 1993; Cook et al., 1997) have pointed that composting was responsible for degrading cross-linkages between monomers and afterwards degradation of these products should continue in soil leaving no toxic residue.

However, as previously mentioned, the long degradation time of SAP and the toxicity of intermediate products of SAP decomposition have promoted the search for new less harmful materials.

- Among all the manufacturing processes involved in the production of the materials that compose diapers, this is the most important in terms of pollution. The production of SAP requires high quantities of water, fuel and natural gas. Additionally, the production of SAP is the main responsible for the emissions of CO₂, CH₄, SO₂ and NO₂ during the production of disposable diapers (Aumônier and Collins 2005).
 - Other components of the disposable diapers are polypropylene, polystyrene, elastics, adhesives, and plastic bags for packaging, which derive from fossil fuels. Their main impacts are related to the emissions of CO₂, CH₄, SO₂ and NO₂ (Aumônier and Collins 2005).
 - To produce a ton of disposable baby diapers 1167.82 kg of materials, 440 L water and 723.9 kWh are consumed and 100 kg of waste are also produced (Aumônier and Collins 2005).
- #### 2. During the commercialisation process and use: the environmental impact associated to the transport, commercialisation and use of disposable diapers is limited to energy consumption, and gas emissions related to transportation and infrastructures maintenance.
- #### 3. During treatment and disposal.
- In case of landfilling, the main impacts are the use of land, methane emissions and possible leachate to groundwater due to the presence of organic wastes. Disposal of organic waste without a pre-treatment may also entail a risk for human health (WEN, 2003).
 - The main impacts of waste incineration are emissions of pollutants to the atmosphere, generation of contaminated wastewater and generation of contaminated ashes (Hester and Harrison, 1994). The main gases produced due to incineration of diapers are greenhouse gases. However, considering that their composition includes several polymers and organic compounds, their incineration may generate other more pollutant substances, such as Cl and CO (Riber, 2007).

Table 5. Environmental impacts derived from the use of disposable diapers during the first 2.5 years of a child's life considering an average number of 4.16 changes per day

Impact category	Unit	Mixed scenario*	Geigy scenario*
Abiotic resource depletion	Kg Sbeq	4.82	4.85
Global warming	Kg CO ₂ eq	626.0	602.0
Ozone layer depletion	Kg CFC ⁻¹¹ eq	0.000261	0.000202
Photochemical oxidation	Kg C ₂ H ₂ eq	0.174	0.163
Acidification	Kg SO ₂ eq	3.78	3.79
Eutrophication	kg PO ₄ ³⁻ eq	0.338	0.337
<i>Human toxicity**</i>	<i>kg 1,4-DB eq</i>	<i>49.4</i>	<i>48.9</i>
<i>Fresh water aquatic ecotoxicity</i>	<i>Kg 1,4-DB eq</i>	<i>7.01</i>	<i>5.98</i>
<i>Terrestrial. ecotoxicity</i>	<i>Kg 1,4-DB eq</i>	<i>1.92</i>	<i>1.9</i>

Source: Aumônier and Collins (2005).

*The original source analyses two scenarios in relation to excreta produced by children between 0 and 24 months, according to different references.

**Italics indicate less developed impact methodologies according to the original source.

Table 5 summarises the main environmental impacts related to disposable diapers, according to a life cycle analysis.

Treatment options

As discussed above, most of the disposable diapers have landfills or waste incinerators as their final destination. However, a number of alternative treatments are being experienced in several countries, as explained below.

- **Mechanical–biological treatment (MBT):** MBT includes two stages. Initially, in the mechanical treatment, some recyclable materials are separated by means of several different methods (manual separation, mechanical sieving, magnets, Foucault separators, etc.). Bulky materials are also manually separated. Afterwards, the remaining materials (mainly biowaste) undergo a biological treatment, which may include aerobic and anaerobic stages or the combination of both. After the biological treatment, biowaste remains stabilized, with a reduced volume and low moisture content. Normally, the compost obtained from MBT has a low quality and it is difficult to commercialize (Slater and Frederickson, 2001). However, these treatments considerably reduce the rejected fraction of municipal solid waste, and the environmental problems associated with this fraction (mainly odours, leachate and reactivity) before its final destination in a landfill. MBT have been used for years all over the world. In Europe, the countries where this system has been applied more widely are Spain, Italy and Germany (Archer et al., 2005).
- **Mechanical separation and recycling of the different fractions:** the separation of the different recyclable fractions included in diapers (organic matter, plastics, cellulose, SAP) has been experienced in several municipalities in the United States of America, Asia and Europe by the

Knowaste company (Knowaste, 2009). Diapers are collected separately and transported to a treatment plant, where they are shredded, washed and their components separated. The resulting materials are: plastics, deactivated SAP, compacted cellulose fibres and composted biowaste. According to Knowaste, this process can divert up to 84% of the materials from landfills and waste incinerators. The major disadvantage of this process is its high cost.

- **Anaerobic digestion:** it consists of anaerobic digestion of waste with a high content of organic matter (such as kitchen waste, food packaging, diapers, etc.) and the transformation of biogas into electricity. The resulting digested organic matter is then treated by an aerobic process, where it is transformed into compost. Several experiences of this kind are being undertaken in Toronto (Canada) and Brecht (Belgium) (Gellens et al., 1995; Forkes 2007), where diapers and biowaste are collected together, and subsequently treated in an anaerobic plant.
- **Composting:** Since the 1990s several laboratory experiments have been undertaken in relation to composting of disposable diapers and their compounds. Despite the scale of these experiences is often small, and the fact that the majority of them focuses on very specific parts of the process, in general they show positive outcomes (Table 6). In addition, since 1998, in the Bapaume region (France), diapers are collected together with biowaste and composted (European Commission, 2000a). Collection is performed on a door-to-door basis, and includes 20 000 households. Wastes are carried to the Bapaume composting plant, with a capacity of 7000 tons year⁻¹, where they undergo an aerobic composting process and a subsequent maturation stage (SMRB, 2007). High-quality compost is obtained because of the good separation in the households.

Other alternatives to disposable diapers are the use of reusable diapers (which can be made of several fabrics and

Table 6. Summary of different scientific reports in relation to biodegradation of disposable diapers

Authors	Year	Objective	Conclusions
Stegmann et al.	1993	To study the fate and effects of hydrated SAP in landfills and during aerobic composting	SAP caused no adverse effects on the degradation of diapers. Most of the material remained associated with the diaper pad and surrounding waste, whereas a small part (less than 6.4%) was biodegraded.
Gerba et al.	1995	To study the presence of enteric pathogenic viruses and protozoan parasites in municipal waste	No viruses or intact nucleic acid are detected after a composting process of 175 days.
Cook et al.	1997	To study the composting process of SAP together with municipal waste	During the composting process only low-molecular-weight polymers were degraded (around 8% of total polymers), which are those that have demonstrated a greater mobility potential in soils. For the rest of polymers the structural integrity of the polymer chains was maintained during the composting process.
MacLeod et al.	1998	To analyse the effects of composting with and without diapers in barley and potato crops.	The observed rise in the yields of forage is similar using both types of compost. There is a lack of studies regarding absorption of heavy metals by potatoes.
Espinosa et al.	2003	To study the biodegradability of diapers	The biodegradation of diapers takes place in aerobic conditions at temperatures above 60°C and pH lower than 5.8. In these conditions, organic materials decrease by 56% and nitrogen concentration increases by 48%.

have to be sanitized after each use) or the use of compostable diapers (made of biodegradable materials).

Composting with the organic fraction of municipal solid waste

To assess the possibility of the composting of used disposable diapers with the OFMSW from source-separation collection systems, a full-scale experiment was carried out. The details of the experience are explained below.

Methodology

Composting process: The composting process was carried out in the composting plant of 'Mancomunitat la Plana'. This plant is located in Malla (Barcelona, Spain) and collects organic waste from door-to-door collection systems implemented in all the municipalities included in this Mancomunitat (Tona, Balenyà, Taradell, Calldetenes, Viladrau, Folgueroles, Seva and Roda de Ter in the province of Barcelona). The plant is located in a rural area and the nearest neighbourhood is a small industrial area. Particular households are at a distance of approximately 2 km. The present capacity of the plant is close to 100 tonnes year⁻¹. Pruning waste from these municipalities is used as bulking agent.

Two different piles were built with and without disposable diapers. Unfortunately, only one replication could be carried out for both experiments because of the amount required of materials (OFMSW and diapers). It is evident that more research would be necessary to cover possible seasonal variations of both diapers and OFMSW.

The following steps were followed to build the two piles.

1. Main substrate for composting was the source-separated OFMSW. The waste came from municipalities with a door-to-door separate collection scheme and it was composed of kitchen residues and garden trimmings. The level of impurities of the OFMSW was lower than 1% (Agència de Residus de Catalunya, 2009). The main characteristics of the used feedstock are shown in Table 7. The disposable used diapers were obtained from the same source separation collection system. They were shredded to 5–10 cm pieces before composting.
2. OFMSW (16 150 kg) was mixed with bulking agent (7590 kg) consisting of shredded pruning wastes in a volumetric ratio 1 : 1 to ensure an adequate level of porosity. This mixture was considered the composting experiment without diapers.
3. OFMSW (12 720 kg) was mixed with shredded diapers (555 kg) to obtain 3% weight percentage of diapers in the OFMSW, which is considered representative of the Spanish use of diapers and the generation of the

Table 7. Properties of the used organic fraction of municipal solid wastes (once mixed with bulking agent in a volumetric ratio 1:1)

Parameter	Value
Dry matter content (%)	42.3
Organic matter content (% dry basis)	74.0
pH	4.80
Electrical conductivity (mS cm^{-1})	4.50
Nitrogen (Kjeldahl) (% dry basis)	1.70
C/N ratio	24
Respiration index ($\text{mg O}_2\text{g}^{-1}\text{ OM h}^{-1}$)	5.43
Bulk density (kg^{-1}L)	0.44
Air-filled porosity (%)	48.2
Impurities (%)	<1

OFMSW, as previously explained. This mixture was also mixed with the same shredded bulking agent (5450 kg) in a volumetric ratio 1:1. The resulting mixture was considered the composting experiment with diapers.

Both mixtures were composted in a static forced-aerated covered composting reactor for 5 weeks (active decomposition stage). During this stage all leachate produced were recirculated into the pile to adjust the moisture content. Afterwards, a non-covered windrow composting system was used for an 18-week additional curing process. Both curing piles were built according to the windrow method (Haug, 1993) with a trapezoidal shape of the following approximate dimensions: base: 4 m; height: 2 m; length: 10–15 m. During the curing process, material was turned once a week. No leachate was observed during the entire curing phase. After the curing process, material was sieved to 10 mm to obtain the final compost. The entire composting experiments lasted from April to October (2008).

To monitor the composting process of both materials during the force-aerated decomposition stage, temperature was daily measured (on-line) *in situ* at two different depths, 400 and 1000 mm, in four different points. In this stage, temperature values are presented as average values of the different monitored points of the pile (Figure 1). Standard deviation of temperature values was within 5–10%. The force-aerated system was designed to provide air to ensure aerobic conditions (oxygen concentration in exhaust air higher than 10%). During the curing stage, temperature and oxygen were measured only at days 43, 53, 83 and 168. In both stages, temperature was measured using a temperature probe (Pt-100; Desin Instrument, Barcelona, Spain), whereas oxygen concentration was measured using an oxygen sensor (QRAE Plus; Sensotran S.L., Barcelona, Spain) connected to a portable aspiration pump.

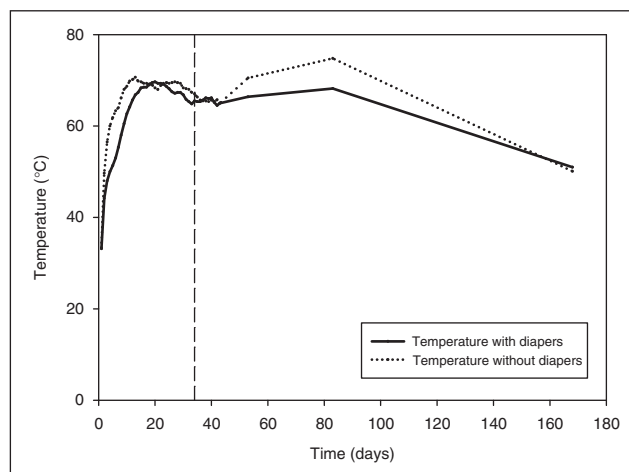


Figure 1. Evolution of temperature during the composting process of the organic fraction of municipal solid wastes, with and without diapers. Vertical dotted line separates decomposition (forced aeration process) from maturation (turned pile process) stages.

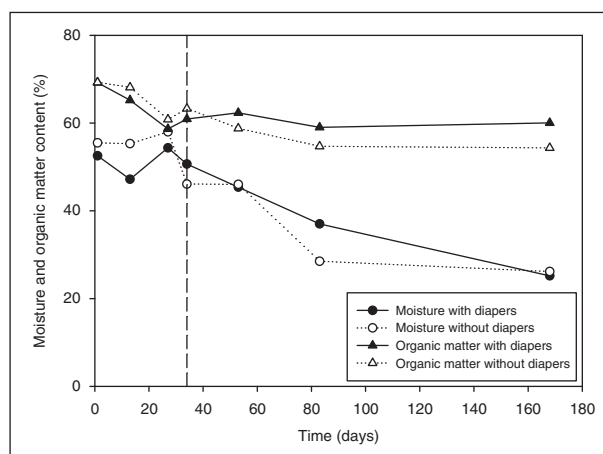


Figure 2. Evolution of moisture and organic matter contents during the composting process of the organic fraction of municipal solid wastes, with and without diapers. Vertical dotted line separates decomposition (forced aeration process) from maturation (turned pile process) stages.

Sampling for analysis of compost was taken at days 1, 13, 27, 34, 53, 83 and 168 in both piles. Sub-samples of 5 kg of the whole material were extracted from four points of each pile. The four sub-samples were mixed manually to obtain a representative sample of each pile. Moisture, organic matter content and respiration index represented in Figures 2 and 3 were determined in an aliquot of at least 1 kg of this representative sample. The final compost samples characterized in Table 8 were obtained using the same procedure after sieving the material to 10 mm.

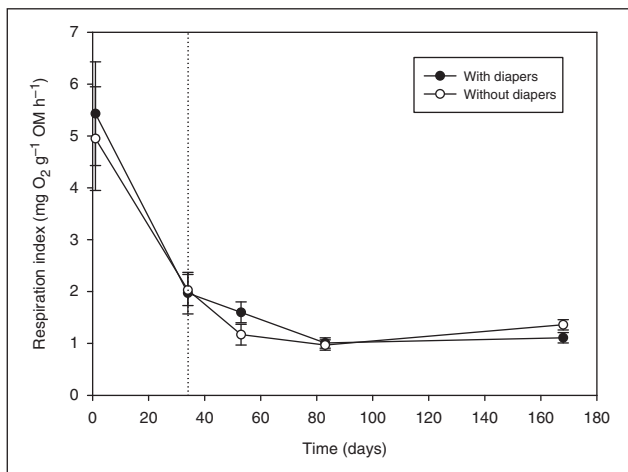


Figure 3. Evolution of respiration index during the composting process of the organic fraction of municipal solid wastes, with and without diapers (standard deviation for respiration index triplicates is represented for each point). Vertical dotted line separates decomposition (forced aeration process) from maturation (turned pile process) stages.

Analytical methods: Dry matter and moisture content, organic matter content, pH, electrical conductivity, total Kjeldahl nitrogen, C/N ratio and bulk density were determined in duplicates from the representative sample obtained as previously explained and according to the US Department of Agriculture and the US Composting Council (2001). A Dewar[®] self-heating test was used as a measure of compost maturity (US Department of Agriculture and US Composting Council, 2001; Weppen, 2002). Air filled porosity (AFP), also referred in literature as free air space (Agnew and Leonard, 2003), is expressed as the ratio of air-filled pore volume of the sample to total sample volume. AFP was *ex situ* measured with a self-made constant volume air pycnometer according to the description of Oppenheimer et al. (1996). AFP data is presented as an average of a triplicate measure.

Pathogen indicators (*Salmonella* and *E. coli*) and heavy metal content (chromium, nickel, lead, copper, zinc, mercury, cadmium and chromium VI) were determined in final compost samples by an external laboratory (Applus Agroambiental S.A., Lleida, Spain).

Phytotoxicity was determined by means of the germination index. *Cucumis sativus* and *Phoenix dactylifera* seeds were used in this test. The germination index was determined according to standard methodologies (Tiquia et al., 1996; Tiquia and Tam, 1998). Germination indices were calculated using three replications.

To monitor the activity and stability of the material, the respiration index was determined. A static respirometer was built according to the original model described by Iannotti et al. (1993, 1994) and following the modifications and recommendations given by Standard Methods (US Department of Agriculture and the US Composting

Council, 2001). The configuration of the respirometer can be found elsewhere (Barrena et al., 2005). Approximately 250 mL of sample were placed in a 500 mL Erlenmeyer flask on a nylon mesh screen that allowed air movement under and through the solid samples. The set-up included a water bath to maintain the temperature at 37 °C during the respirometric test. Prior to the assays, samples were incubated for 24 hours at 37 °C. Throughout the incubation period the samples were aerated with previously humidified air at the sample temperature. The drop in oxygen content in a flask containing a sample was monitored with a dissolved oxygen meter (Lutron 5510; Lutron Co. Ltd., Taiwan) connected to a data logger. The rate of respiration of the sample based on organic matter content (OM) was calculated from the slope of the oxygen level decrease according to the standard procedures (Iannotti et al., 1993). Results of the respiration index are expressed as milligrams of O₂ consumed per hour and per gram of organic matter and are presented as an average value of three replicates with standard deviation.

Results and discussion

Composting process performance: Figure 1 shows the evolution of temperature during the entire process. In both cases (with and without diapers), thermophilic temperatures were reached, which was probably due to the high biodegradability of OFMSW coming from source-separated collection systems (Ponsá et al., 2008; Ruggieri et al., 2008). In both piles, it can be concluded that the totality of the material was exposed to temperatures in the thermophilic range and consequently met the international requirements on compost sanitation, which are based on time-temperature conditions (US Environmental Protection Agency, 1995; European Commission, 2000b). In the case of oxygen content, both piles showed values of oxygen concentration up to 10% during the entire composting experience (data not shown), which are related to the prevalence of aerobic conditions (Haug, 1993).

Figure 2 shows the evolution of moisture and organic matter content during the composting processes. As observed, both evolutions are very similar. Thus, moisture did not present a clear trend during the decomposition stage; however in no case were the variations of moisture values in this stage were important. As the composting system was covered, water evaporation was prevented and most of the condensed water vapour returned to the material. Moreover, in order to prevent moisture loss, leachate produced was again recirculated during the decompositional phase. On the contrary, when the material was taken out of the composting reactor for curing in non-covered windrows, water evaporation was considerable and moisture content became limiting. This is especially relevant since the curing process took place during summer conditions, as it has been reported

Table 8. Properties of the final compost obtained with and without diapers. Spanish legislation corresponds to Class A compost according to Ministerio de la Presidencia (2005)

Parameter	Compost without diapers	Compost with diapers	Spanish legislation (Class A)
Dry matter content (%)	74.3	76.0	60–70
Organic matter content (% dry basis)	63.1	56.0	>35
pH	9.05	8.05	No value
Electrical conductivity (mS cm ⁻¹)	2.01	1.98	No value
Nitrogen (Kjeldahl) (% dry basis)	2.33	1.94	No value
C/N ratio	15	16	<20
Respiration index (mg O ₂ g ⁻¹ OM h ⁻¹)	1.40	1.57	No value
Bulk density (kg L ⁻¹)	0.36	0.40	No value
Air filled porosity (%)	61	57	No value
<i>E. coli</i> (CFU g ⁻¹)	<10 (absence)	20 (absence)	<1000
<i>Salmonella</i> (Presence/absence in 25g)	Absence	Absence	Absence
Germination index <i>Cucumis sativus</i> (%)	94	133	No value
Germination index <i>Phoenix dactylifera</i> (%)	98	91	No value
Chromium (mg kg ⁻¹ , dry matter basis)	9	14	70
Nickel (mg kg ⁻¹ , dry matter basis)	9	14	25
Lead (mg kg ⁻¹ , dry matter basis)	28	26	45
Copper (mg kg ⁻¹ , dry matter basis)	44	41	70
Zinc (mg kg ⁻¹ , dry matter basis)	156	200	200
Mercury (mg kg ⁻¹ , dry matter basis)	0.06	0.09	0.4
Cadmium (mg kg ⁻¹ , dry matter basis)	0.3	0.3	0.7
Chromium VI (mg kg ⁻¹ , dry matter basis)	<0.50	<0.50	0

that there is a correlation between composting performance and environmental conditions (McCartney and Eftoda, 2005). In relation to organic matter content, this parameter shows a decrease during the first active decomposition stage to reach a plateau during the curing stage. This trend has been previously observed in other studies related to OFMSW composting and it can be considered as the typical evolution (Ruggieri et al., 2008).

Figure 3 presents the evolution of the respiration index during the entire composting process. Again, the values observed between OFMSW with and without diapers were very similar. As observed in Figure 3, the most important part of biological activity reduction expressed as respiration index occurred during the decomposition stage, when it changed from 5–6 mg O₂g⁻¹ OM h⁻¹ to approximately 2 mg O₂g⁻¹ OM h⁻¹. This is an important reduction of activity achieved in a relatively short composting time (5 weeks). Afterwards, in the first part of the curing stage, an additional decrease of respiration activity was observed to reach values near 1 mg O₂g⁻¹ OM h⁻¹, which are similar to those of stable compost (Barrena et al., 2006a). However, during the last part of the curing stage (from day 80 to day 168), no decrease in biological activity was observed (Figure 3). This fact was probably due to a moisture limitation that prevented the normal development of composting microbial communities.

Anyway, this fact highlights the suitability of respiration techniques for the monitoring of processes involving biological treatment of organic solid wastes as previously reported (Ponsá et al., 2008; Barrena et al., 2009). On the contrary, other indirect parameters of biological activity such as temperature are not valid to monitor the composting process at full-scale (Figure 1), because of the thermal inertia effect associated to large composting masses that prevents temperature to decrease (Barrena et al., 2006b).

Final compost properties: Table 8 shows the complete characterization of the final compost obtained with and without diapers. Although some parts of non-degraded pieces of diapers could be visually observed in the material with diapers, they were completely removed during the sieving process. For comparison, in Table 8 the values required for Class A compost (suitable for agronomical purposes) according to the current Spanish legislation (Ministerio de la Presidencia, 2005) are also presented, although it is necessary to comment that at present the requirements for compost in Spanish legislation are being discussed and revised.

The general conclusion to be extracted from Table 8 is that both products are sanitized, stable and of good quality. Furthermore, the differences found between both materials

(with and without diapers) are minimal. They are more specifically described here.

1. General properties are adequate for OFMSW compost, with a high content of organic matter and a significant amount of nitrogen. C/N ratios are around 15 to 16, which are also correct for good compost (Bernal et al., 1998). As previously discussed, the property that is far from legislation is moisture content, which is lower than required according to the composting process carried out under limiting conditions of this parameter. Finally, the low values observed in the electrical conductivity are related to a low salt content in both composts. This is especially interesting as SAP is believed to be composed of sodium compounds.
2. Stability (respiration index) reached is in accordance to the values presented in Figure 3. Stability is very close to that of what is considered stable compost, although in the last part of the curing stage under moisture-limiting conditions, this value remained practically constant. The slight increase observed in the respiration value of the final compost sample in comparison with that of the final sample showed in Figure 3 can be explained according to the concentration of organic matter after the sieving process that implies the removal of bulking agent and non-compostable materials present in the OFMSW (Ruggieri et al., 2008). On the other hand, maturity grade (III) corroborates the results obtained with the respiration index and with some previous studies (Barrena et al., 2006c).
3. Compost presents no phytotoxicity according to the values of germination indices obtained for both *Cucumis sativus* and *Phoenix dactylifera*. Typically, compost with values of germination index over 80% is assumed to be non phytotoxic (Tiquia et al., 1996; Tiquia and Tam, 1998).
4. Sanitation has been highly effective and none of the pathogenic micro-organisms used as indicators have been detected. It is evident that the temperature reached and the number of turnings during the curing stage has a positive effect on sanitation.
5. In relation to heavy metals content, it is clear that the levels detected for both materials are very low. Both composts are classified into Class A compost, which can be used for agriculture purposes. The sole exception would be the zinc content in the compost with diapers, which is equal to the limit value for Class A. As zinc is commonly used in pomades for baby skin care (Runeman, 2008; Visscher, 2009) and as supplement for baby milk powder (Ikem et al., 2002), it can be hypothesized that the origin of this zinc is diapers, although this fact should be confirmed in further studies. For instance, there are other hypotheses to explain the relatively higher content of zinc in the compost with

diapers, since this metal is commonly used and can be present in shredding machines used for diapers, metal containers used for diapers accumulation, etc. Moreover, it has been reported that bulking agent can also add a baseline content of zinc that could affect both composts (Kim et al., 2008; Smith, 2009).

Conclusions

From the literature reviewed in this study, it can be concluded that disposable diapers are an important part of the overall stream of municipal solid wastes. Although diapers have received little attention in research studies and their main destination is landfill or incineration, several alternative management options have been explored in literature showing promising results in terms of recovery improvement and recycling.

The co-composting process of the source-separated organic fraction of municipal solid waste with disposable diapers at full-scale has shown no technical problems in the biological process in terms of stability, phytotoxicity and sanitation of the resulting compost. The sole exception for compost quality when diapers were included was a slightly higher concentration of zinc in compost. Another uncertainty derives from the unknown behaviour of superabsorbent polymers in soil. These two aspects, jointly with the research for new less toxic materials that may be used as superabsorbents, should be the objectives of further research on this field.

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