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Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study

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ABSTRACT

The aim of this study is to compare, from an environmental point of view, different alternatives for the management of municipal solid waste generated in the town of Castellón de la Plana (Spain). This town currently produces 207 ton of waste per day and the waste management system employed today involves the collection of paper/cardboard, glass and light packaging from materials banks and of rest waste at street-side containers.

The proposed alternative scenarios were based on a combination of the following elements: selective collection targets to be accomplished by the year 2015 as specified in the Spanish National Waste Plan (assuming they are reached to an extent of 50% and 100%), different collection models implemented nationally, and diverse treatments of both the separated biodegradable fraction and the rest waste to be disposed of on landfills.

This resulted in 24 scenarios, whose environmental behaviour was studied by applying the life cycle assessment methodology. In accordance with the ISO 14040-44 (2006) standard, an inventory model was developed for the following stages of the waste management life cycle: pre-collection (bags and containers), collection, transport, pre-treatment (waste separation) and treatment/disposal (recycling, composting, biogasification + composting, landfill with/without energy recovery). Environmental indicators were obtained for different impact categories, which made it possible to identify the key variables in the waste management system and the scenario that offers the best environmental behaviour. Finally, a sensitivity analysis was used to test some of the assumptions made in the initial life cycle inventory model.

1. Introduction

The life cycle assessment (LCA) (ISO 14040-44, 2006) methodology provides an excellent framework for evaluating municipal solid waste (MSW) management strategies. Many of its applications in this field are focused on the use of the LCA methodology as a decision support tool in the selection of the best MSW management strategy (from an environmental point of view) in a wide range of countries including Italy (Buttol et al., 2007; Brambilla Pisoni et al., 2009; Scipioni et al., 2009; Cherubini et al., 2009; de Feo and Malvano, 2009), Spain (Bovea and Powell, 2006; Guereca et al., 2006), Sweden (Eriksson et al., 2005), Germany (Wittmaier et al., 2009), UK (Emery et al., 2007), Turkey (Banar et al., 2009), USA (Contreras et al., 2008), Singapore (Khoo, 2009) and China (Zhao et al., 2009), among others.

The fact that the application of the LCA methodology to the field of waste management has recently become more generalised can also be seen by the growth in the amount of software developed for this purpose, such as IWM-2 (McDougall et al., 2001), WISARD, (1999), ORWARE (Eriksson et al., 2002), LCA–IWM (den Boer et al., 2007, DST–MSW (Thorneloe, 2006), EASEWASTE (Kirkeby et al., 2006) or WAMPS (Stenmarck, 2009). Although built upon a common methodological base, each of these computer applications uses its own inventory model for the main processes involved in waste treatment. Nevertheless, as stated by Winkler and Bilitewski (2007), efforts need to be made to increase the transparency of the data and to lower the degree of uncertainty in these models in order to obtain more robust results.

In this work, the LCA methodology was applied to assess, from an environmental perspective, different alternative scenarios for MSW management in Castellón de la Plana (Spain) that make it possible to reach the targets set on a nationwide scale for the year 2015 (PNIR, 2008). The proposed alternative scenarios were based on a combination of the following elements: (1) targets proposed

Abbreviations: EPS, expanded polystyrene; HDPE, high-density polyethylene; IWM, integrated waste management; LCA, life cycle assessment; LCI, life cycle inventory; LDPE, low density polyethylene; LPB, liquid packaging board; MRF, material recovery facility; MSW, municipal solid waste; PET, polyethylene; PP, polypropylene; PS, polystyrene; PVC, polyvinylchloride; PNIR, Plan Nacional Integral de Residuos (Spanish National Waste Plan); TS, transfer station.

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in the Spanish National Waste Plan (in Spanish, *Plan Nacional Integrado de Residuos* – PNIR, 2008) for the year 2015 (assuming they are fulfilled to an extent of 50% and 100% in the so-called *pessimistic* and *optimistic* scenarios, respectively), (2) three different models of collection implemented nationwide, and (3) different treatments for the separated biodegradable fraction (composting or biogasification) and the rest waste to be sent to landfills (with/without energy recovery). This results in 24 scenarios whose environmental behaviour is analysed from a life cycle perspective. In the inventory phase of the LCA methodology, efforts were made to obtain a specific inventory model that is well suited to the case study by gathering field data directly from the companies responsible for waste management. In order to test some of the assumptions made in the life cycle inventory, a sensitivity analysis were carried out to discuss how results were affected by changing those assumptions.

2. Description of the current system of MSW management used in Castellón de la Plana

The town of Castellón de la Plana is situated on the east coast of Spain. It has a population of 172 110 inhabitants and in 2007 household waste was generated at a rate of 1.15 kg/person/day. The composition of the waste is shown in Table 1.

At the present time, its model of household waste collection is based on a combination of the selective collection of glass, paper/cardboard and packaging at materials banks and street-side collection of the rest waste. In 2007, with this management system, 7.47% of all waste was collected at materials banks, the composition being as follows:

- The 1.43% glass, which is used to produce cullet in a glass sorting plant; from there the cullet is then sent to glass manufacturing companies.
- The 5.02% paper/cardboard, which is sent to a paper/cardboard sorting plant where it is shredded and packed and later taken to paper mills.
- The 1.02% packaging, which is taken to a packaging separation plant, where the HDPE, LDPE, PET, liquid packaging board (LPB), and ferrous and non-ferrous metals are separated out.

The remaining 92.53% belongs to the rest waste that is collected at street-side containers. After being compacted at a transfer station (TS), this waste is taken to a material recovery facility (MRF), where the following fractions are separated out:

– Organic material that will be used to produce compost, and
– Recyclable fractions (paper/cardboard, plastic, ferrous and non-ferrous metals), which will be sent to recycling plants.

Lastly, the different reject materials obtained at the different facilities are compacted in bales and sent to be deposited on a landfill without energy recovery.

Table 1
Composition of MSW in the study area.

Fraction	Percentage (%)
Organic material	57
Paper/cardboard	15
Plastic	10
Glass	7
Metal	4
Textile	4
Others	3

Table 2
Efficiency of waste pre-treatment and treatment facilities.

	Fractions recovered	Percentage (%)
Glass sorting plant	Cullet	90.00
	Waste	
	Metal	3.00
	Glass	7.00
Paper sorting plant	Paper	60.00
	Cardboard	38.00
	Waste	
	Plastic	2.00
Packaging sorting plant	HDPE	8.65
	LDPE	12.02
	PET	18.52
	Ferrous	0.65
	Non-ferrous	11.91
	Mix	12.45
	LPB (cartons)	6.81
	Waste	29.00
Material recovery facility	Paper/cardboard	2.29
	Metal	2.19
	Plastic	0.37
	Organic material	44.68
	Waste	50.46

These data, together with the efficiency of the waste pre-treatment and treatment facilities (Table 2), are then taken into account to obtain the current model shown in Fig. 1.

3. Alternative MSW management scenarios

Recent EU legislation concerning solid waste has made it necessary to adjust national environmental laws. In Spain, alternative scenarios to the present MSW management system described in Section 2 must be defined in order to come adapt to the recently implemented National Waste Plan for 2008–2015 (PNIR, 2008). One of the objectives of this scheme, among other things, is to reduce the percentage of waste that is sent to sanitary landfills in Spain. To achieve this, it sets several collection targets to be reached during the time it is in force (see Table 3) as well as other objectives related to recycling and recovery (see Table 4).

The alternative scenarios that make it possible to reach, or to come close to reaching, these targets were defined by combining different parameters, as can be seen in Fig. 2.

3.1. Models of selective collection

In Spain, MSW is collected using a number of different systems. The results of a survey covering all Spanish towns and cities with over 50,000 inhabitants were used to define the three systems shown in Table 5 as being the most widely used on a national scale. They can be distinguished by the fractions that are sorted by the householder (rest waste, glass, paper/cardboard, packaging and/or organic) and the distance to the collection point (street-side containers or materials banks at high-density [close-to-home drop-off]) (Gallardo et al., 2008).

3.2. Biological treatments

Different methods of treatment can be used to recover organic material. In our study, the biological treatments of composting (A) and biogasification (B) were considered.

3.3. Final disposal of waste

For the final disposal of waste, two options were taken into account: landfills without energy recovery (a) and landfills with

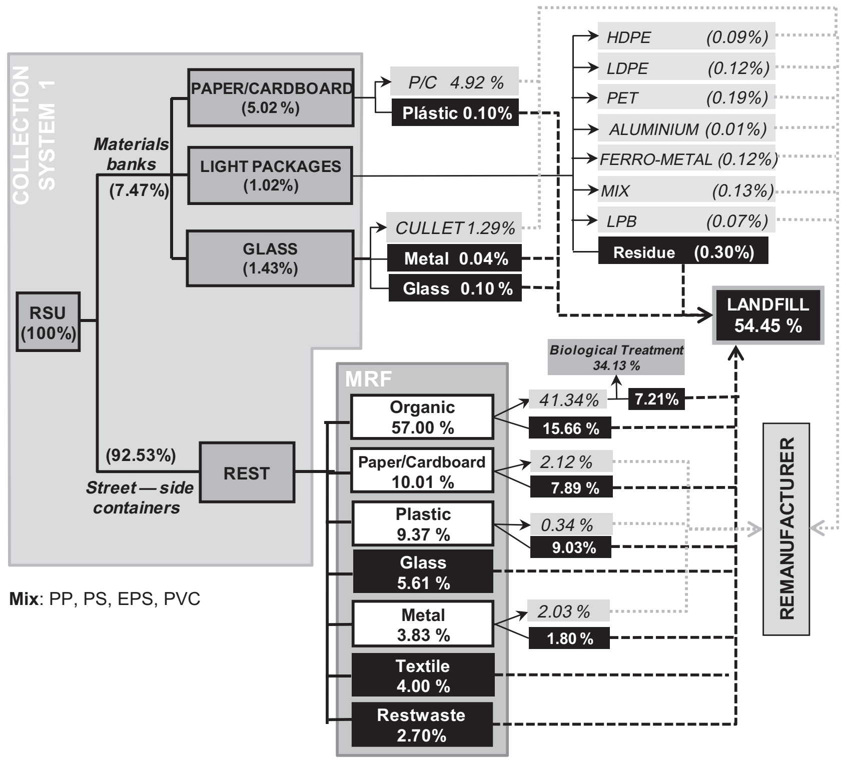

Fig. 1. Baseline scenario: current system of MSW management used in Castellón de la Plana.

Table 3
Collection target: increase in the number of tons to be collected selectively, as established in the PNIR for 2015, and taking the year 2006 as the baseline (PNIR, 2008).

	Increases in collection (baseline year 2006) (%)
Paper/cardboard	80
Glass	80
Plastic	100
Metals	100
Organic material	50

Table 4
Recycling and recovery targets required by the PNIR (2008).

Targets in the PNIR 2008–2015	Percentage (%)
Recycling rates by materials:	
Paper/cardboard	60
Glass	60
Metals	50
Plastics	22.50
Recycling rate	55–80
Recovery rate	>60
Biological treatment rate	>50

energy recovery (b). Incineration with energy recovery has not been considered as an alternative option to landfill, because the Municipal Solid Waste Management Plan approved in the area of the case study (Castellón, Comunidad Valenciana, Spain) by now does not consider the incineration option as a treatment and therefore, there is not any incineration facility in this geographical area.

3.4. Extent to which collection targets are fulfilled

Whether the collection targets shown in Table 3 are met or not depends largely on householders response to awareness-raising campaigns aimed at encouraging them to keep household waste to a minimum and to recycle it. In this study, it was assumed that citizens responded in two different ways that give rise to scenarios that can be considered "*optimistic*", where it is assumed that the increases in selective collection shown in Table 3 (1Aa, 1Ab, ..., 3Ba, 3Bb) are fully achieved, or "*pessimistic*", which suppose that half the increases in selective collection shown in Table 3 (1^{*}Aa, 1^{*}Ab, ..., 3^{*}Ba, 3^{*}Bb) are accomplished.

Combining the four parameters described above results in the 24 possible MSW management scenarios shown in Fig. 2.

4. Application of the LCA methodology to the case study

4.1. Stage I: definition of aims and scope

The main aim of this study was to propose alternative systems for MSW management in Castellón de la Plana that make it possible to reach, or to come close to reaching, the goals set out in the recent legislation on waste management. The results of this study can be used as technical support during the decision-making processes by the local authorities, in order to justify the selection of the best alternative waste management system.

As the aim of this study is to describe the environmental properties of the life cycle of a waste management system and its subsystems, the attributional modelling has been chosen (Finnveden et al., 2009).

The scenarios to be analysed can be seen in Fig. 2. They are defined by combining different collection models and systems for treating the biodegradable fraction and the waste to be sent to landfills, while also taking into account different rates of success as regards the fulfillment of the selective collection targets given in Table 3. More specifically, the current model of management shown in Fig. 1 will be compared with those derived from Figs. 3–5.

SCENARIOS	COLLECTION SYSTEM (see Table 5)			TREATMENT			
				BIOLOGICAL TREATMENT		LANDFILL	
	1	2	3	COMPOSTING (A)	BIOGASIFICATION (B)	WITHOUT ENERGY RECOVERY (a)	WITH ENERGY RECOVERY (b)
1Aa - 1*Aa	x			x		x	
1Ab - 1*Ab	x			x			x
1Ba - 1*Ba	x				x	x	
1Bb - 1*Bb	x				x		x
2Aa - 2*Aa		x		x		x	
2Ab - 2*Ab		x		x			x
2Ba - 2*Ba		x			x	x	
2Bb - 2*Bb		x			x		x
3Aa - 3*Aa			x	x		x	
3Ab - 3*Ab			x	x			x
3Ba - 3*Ba			x		x	x	
3Bb - 3*Bb			x		x		x

Fig. 2. Alternative scenarios proposed.

Table 5
Collection systems implemented in Spain: fraction and percentage of collection.

Collection system	Bring system (street-side container)	Bring system (high-density materials banks)
1	Rest waste (89.98%)	Glass (2.26%) Packaging (1.85%) Paper/cardboard (5.51%)
2	Rest waste (86.53%) Packaging (4.29%)	Glass (3.29%) Paper/cardboard (5.89%)
3	Rest waste (79.17%) Putrescible (8.26%)	Glass (3.16%) Packaging (1.97%) Paper/cardboard (7.44%)

Fig. 6 offers a graphic representation of the system boundaries in the form of inputs and outputs. It also shows the different stages to be analysed in our LCA, i.e. pre-collection, collection and transport, pre-treatment, treatment and final disposal.

The functional unit of our system is the management of 1 ton of MSW generated in Castellón with a composition as shown in Table 1.

4.2. Stage II: life cycle inventory

For the pre-collection, collection and pre-treatment stages, a specific inventory model was produced from field data collected

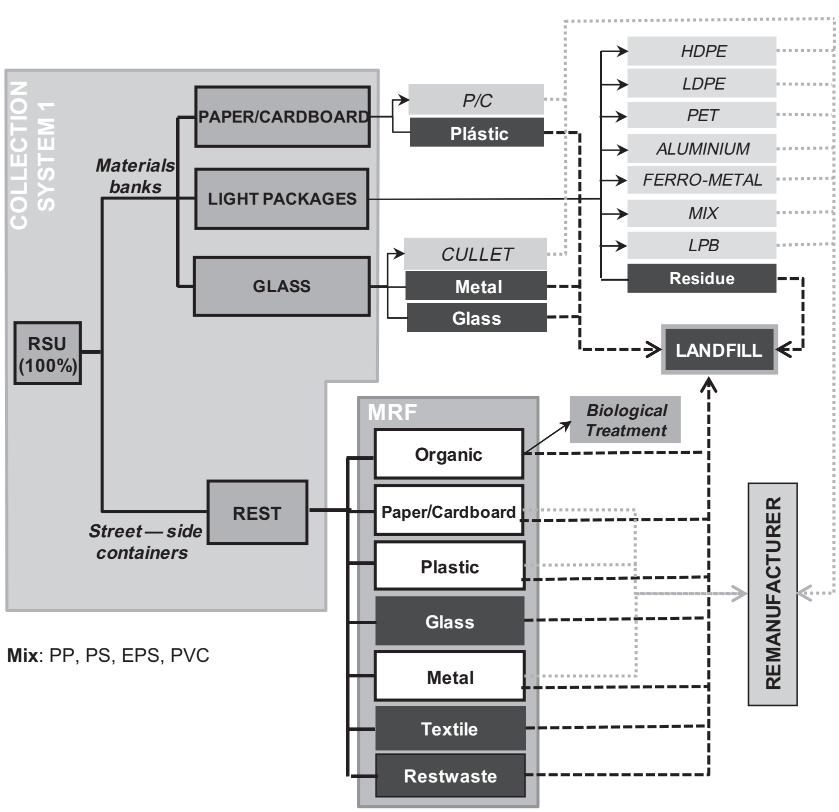

Fig. 3. Scenarios based on collection system 1: 1Aa, 1Ab, 1Ba, 1Bb, 1*Aa, 1*Ab, 1*Ba, 1*Bb.

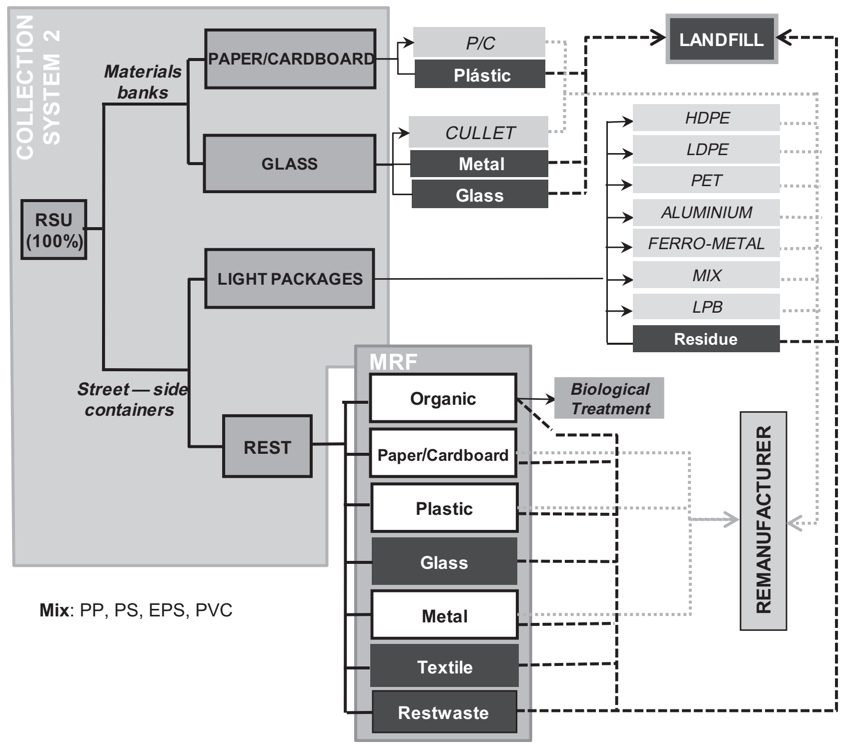

Fig. 4. Scenarios based on collection system 2: 2Aa, 2Ab, 2Ba, 2Bb, 2*Aa, 2*Ab, 2*Ba, 2*Bb.

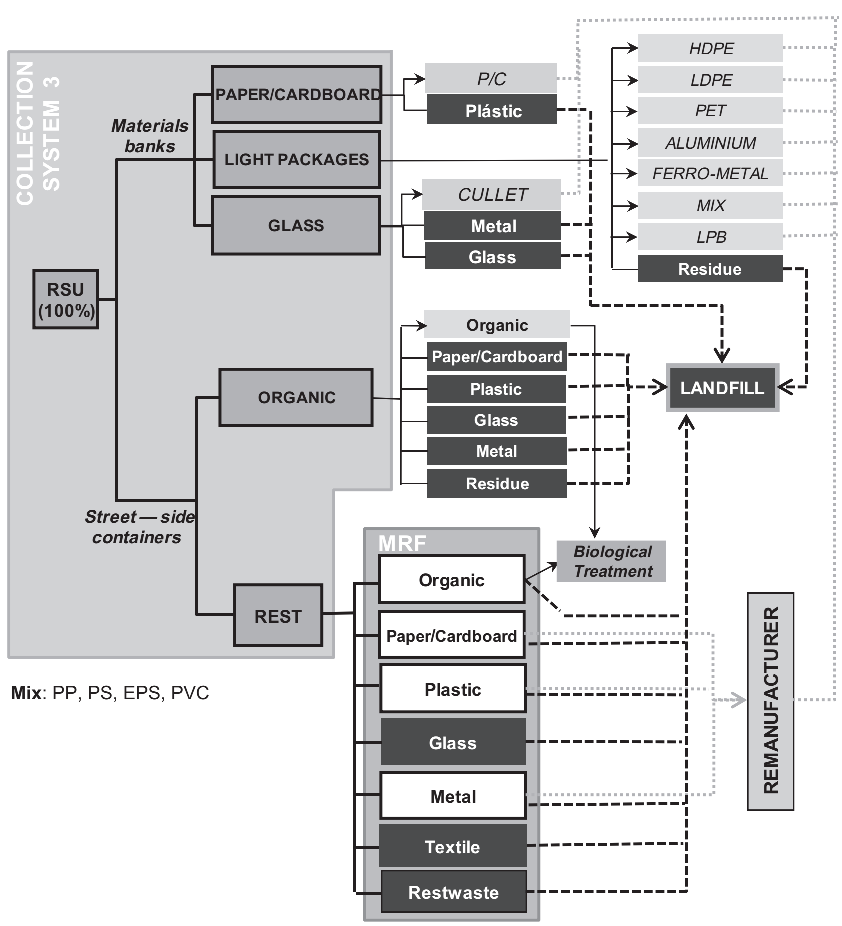

Fig. 5. Scenarios based on collection system 3: 3Aa, 3Ab, 3Ba, 3Bb, 3*Aa, 3*Ab, 3*Ba, 3*Bb.

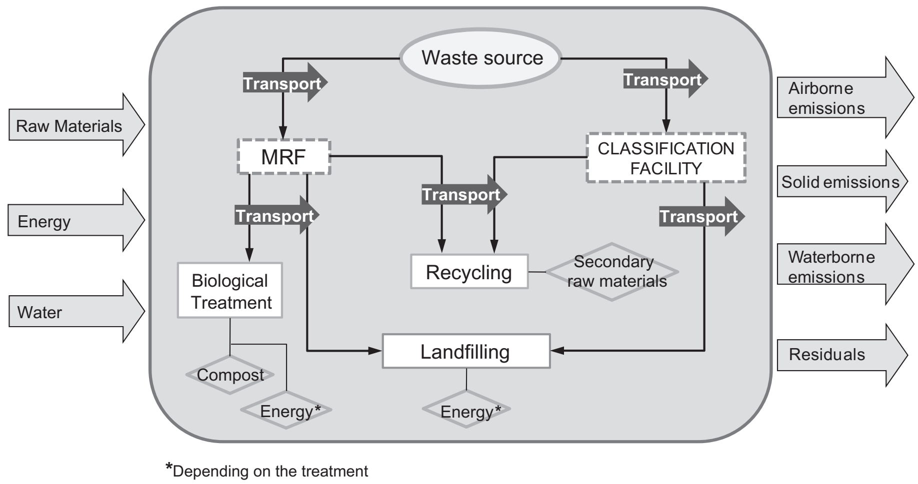

Fig. 6. Scope of the study.

Table 6
Data used to construct the container inventory.

	Volume (l)	Piece – material and process		Weight (kg)
Medium-sized wheelie bin	360	Body	HDPE Injection moulded	17.35
		Auxiliary parts	Stainless steel Forged	1.50
		Two wheels	Rubber Injection moulded	1.15
Large wheelie bins (containers)	1100	Body	HDPE Injection moulded	55.21
		Auxiliary parts	Stainless steel Machined (80%) Forged (20%)	2.50
		Four wheels	Rubber Injection moulded	2.29
Side-loader recycle bin	3200	Body	HDPE Injection moulded	140
		Structure	Stainless steel Machined (70%) Forged (30%)	40.00
Circular igloo-type	3000	Body	HDPE Injection moulded	100.40
		Lifting system	Stainless steel Machined	1.30
		Mouth protection	Rubber Injection moulded	0.260
Metallic container	3000	Body	Galvanised steel Machined (80%) Cold form (20%) Welded (18.8 m)	263.70
		Lifting system	Stainless steel Machined	1.30

Table 7
Fuel consumption during the transport stage.

Shows route	Distance (one way) (km)	l/ton
Origin – glass sorting facility	58	1.96
Origin – paper sorting facility	6.8	0.31
Origin – packaging sorting facility	4.4	0.20
Origin – transfer station	5.9	0.20
Origin – MRF	23.7	0.80
Transfer station – MRF	25	0.48
Glass sorting facility – glass recycling plant	47.6	1.61
Paper sorting facility – paper recycling plant	287	11.11
Packaging sorting facility – HDPE recycling plant	76	2.94
Packaging sorting facility – PET recycling plant	76	2.94
Packaging sorting facility – mixture recycling plant	449	17.38
Packaging sorting facility – LPB recycling plant	290	11.22
Packaging sorting facility – LDPE recycling plant	725	28.06
Packaging sorting facility – aluminium recycling plant	290	11.22
Packaging sorting facility – ferrous metal recycling plant	76	2.94
MRF – composting plant	8	0.20
MRF – paper recycling plant	308	11.92
MRF – plastics recycling plant	283.14	10.96
MRF – ferrous metal recycling plant	66.4	2.57
Glass sorting facility – landfill (metal)	46.9	1.82
Glass sorting facility – landfill (glass)	46.9	1.59
Paper sorting facility – landfill	18.7	0.72
Packaging sorting facility – landfill	22.8	0.58
MRF – landfill (putrescible)	2	0.05
MRF – landfill (paper)	2	0.08
MRF – landfill (plastic)	2	0.08
MRF – landfill (glass)	2	0.07
MRF – landfill (metal)	2	0.08
MRF – landfill (textile)	2	0.08
MRF – landfill (rest waste)	2	0.08
Composting plant – landfill	2	0.05

directly from local companies responsible for the management of the waste produced in the town under consideration in this study. The Ecoinvent (2007) database was used to obtain the inventory data for the materials involved in this study and for final treatments. As this database has been mainly developed for Swiss technologies, in order to adapt it to the Spanish situation, the following changes have been made in the original data:

– The Swiss energetic mix has been substituted by the Spanish mix one (see Table 9).
– The transport distances and characteristics have been updated to the Spanish situation.

Table 8
Electricity, water and fuel consumed by the pre-treatment plants.

	Electricity (kWh/ton)	Diesel (l/ton)	Water (m^3/ton)
Glass sorting facility	8.05	0.53	–
Paper/cardboard sorting facility	3.99	2.58	–
Packaging sorting facility	6.10	0	n/a
Transfer station	1.36	1.76	0.043
Material recovery facility (MRF)	8.11	0.56	0.004
Composting plant	19.67	0.36	0.054

n/a: Data not available.

Table 9
Proportion of the different energy sources used in the generation of electricity in Spain throughout the year 2008 (REE, 2009).

	Percentage (%)
Hydroelectric	7.06
Nuclear	19.44
Coal	16.36
Fuel–oil + gas	3.53
Natural gas	31.48
Hydroelectric	1.46
Wind-power	10.47
Photovoltaic	2.52
Combined cycle	7.68

– The recycling model has been created assuming 1:1 substitution ratio among the avoided primary material production and the production of secondary material.

Only data for biogas and leachate composition have been obtained from McDougall et al. (2001). Section 6 includes a sensitivity analysis to check the influence on the results for applying the Ecoinvent (2007) inventory model vs. McDougall et al. (2001) inventory model, and for modifying the substitution ratio applied in the recycling treatment model.

The inventory data used for each stage of the waste management life cycle are detailed below.

4.2.1. Pre-collection

This stage considers the environmental impact caused by bags of rubbish and containers. An average rubbish bag was taken as being made of 10.17 g of LDPE with a capacity to hold 15.87 l of waste composed of fractions as shown in Table 1. The process of extruding the LDPE used to make the bag consumes 0.746 kWh/kg of LDPE. The bins or containers used to temporarily store the waste were taken as being those detailed in Table 6. Street-side collection is carried out using 360 and 1100 l back-loader containers and 3200 l side-loader containers. High-density collection by means of materials banks, on the other hand, is performed using 3000 l igloo-type containers made of HDPE for the glass fraction and galvanised steel containers for the paper/cardboard and light packages fractions.

4.2.2. Collection and transport

A distinction was drawn between the fuel consumed in the waste collection stage and the amount required to transport it to the next pre-treatment and/or treatment facility. For the collection stage, it was assumed that 2.77 and 6.12 l of diesel were consumed for each ton that was collected, from street-side containers and materials banks respectively. Table 7 shows the fuel consumptions and the distance (one route) for each ton of waste transported to the next pre-treatment or treatment facility, for each of the routes that were considered in the study.

4.2.3. Pre-treatment

In order to complete the inventory for the pre-treatment plants, data were collected directly from the facilities responsible for waste management in the case study. To do so, annual data for the year 2008 were collected and assigned to the functional unit. The electricity, fuel and water consumptions for each type of facility can be seen in Table 8.

Table 9 shows the electricity production mix for Spain for the year 2008 (REE, 2009). The inventory accounts for the electricity production and import, and the electricity losses during the transmission and transformation.

4.2.4. Treatments

Among the possible treatments that can be applied to retrieved materials, this study only considers the recycling of paper/cardboard, glass, plastics, ferrous and non-ferrous waste, and the biogasification and composting of organic material.

The recycling inventory for each fraction have been modelled from Ecoinvent (2007) data, assuming 1:1 substitution ratio among the avoided primary material production and the production of secondary material. The recycling efficiency considered is shown in Table 10 (Rigamonti et al., 2009).

Section 6 includes a sensitivity analysis to check the influence on the results as a consequence of modifying the substitution rate in the recycling model.

Regarding the composting process, 50% of compost is considered as avoided fertilizer while the remaining 50% is applied as a cover material in landfill. According to McDougall et al. (2001), 1 ton of compost is equivalent to 7.1 kg N, 4.1 kg P_2O_5 and 5.4 kg K_2O.

Finally, the biogasification model assumes a production of 190 kWh/ton introduced to the digester (McDougall et al., 2001), that is considered as avoided burden.

4.2.5. Landfill

This study considers two alternative methods of disposing of the residual fraction from the different pre-treatment and treatment plants on landfills: landfills with and without energy recovery. The inventory model used for these processes assumes a production of 250 Nm^3 of biogas for ton of biodegradable fractions and 100 m^3 for ton of residues from the composting processes, and a production of 0.15 m^3 of leachate from landfilled ton. Air emissions for landfill without/with energy recovery and leachate composition were obtained from McDougall et al. (2001).

4.3. Stage III: assessment of the impacts of the life cycle

All the inventory data described in the previous section were modelled using the SimaPro7 (2008) software application. Then, following the methodology proposed by the ISO 14040-44 (2006) standard, environmental indicators were obtained for different im-

Table 10
Recycling efficiency considered in the recycling model (Rigamonti et al., 2009).

Fraction	Recycling efficiency
Steel	90.5
Aluminium	83.5
Glass	100
Paper	89
Plastic	74.5
Organic	37.5

Table 11
Impacts and pollution burden avoided at each of the stages of the waste management life cycle.

Stage	Impact	Burden avoided
Pre-collection	Use of bags and bins	
Collection and transport	Fuel consumption	
Pre-treatment	Fuel, electricity consumption: Sorting of glass, paper/cardboard and packaging waste collected selectively Transfer and sorting of the rest waste collected using street-side collection	
Recycling	Fuel and electricity consumption in recycling operations	Virgin materials avoided for each of the recycled fractions
Biological treatment	Fuel and electricity consumption in composting and biogasification operations	Chemical fertilisers (composting) electrical energy (biogasification)
Landfill	Fuel consumption in operations involving the movement of waste at the landfill	Electrical energy (landfill with energy recovery)

pact categories. The characterisation factors applied to each impact category are those proposed by the CML method (Guinee, 2002). The impact categories that were studied, as well as the units considered for each of them, were: acidification (kg SO_2 eq), eutrophication (kg PO_4 eq), global warming (kg CO_2 eq), ozone layer depletion (kg CFC-11 eq) and photochemical oxidation (kg C_2H_2 eq).

First of all, an analysis was performed to determine the influence exerted by the different stages of the life cycle of the waste management system on each impact category. Table 11 shows what processes are included in each of the stages that were analysed.

Fig. 7 shows these results for the "*pessimistic*" scenarios (1^*Aa, 1^*Ab, ..., 3^*Ba, 3^*Bb), in which 50% of the collection targets

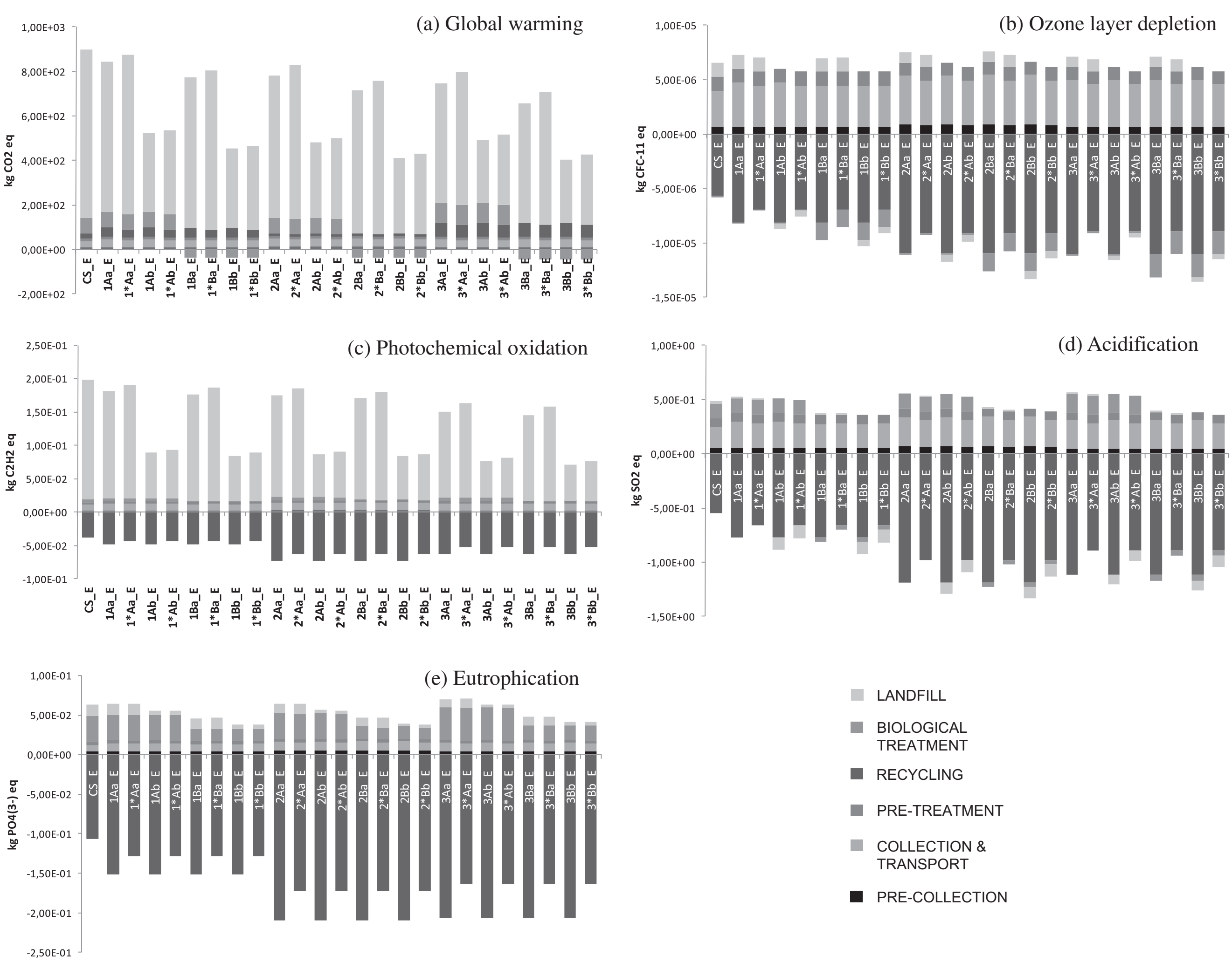

Fig. 7. Contribution made by each stage of the waste management life cycle to each impact category.

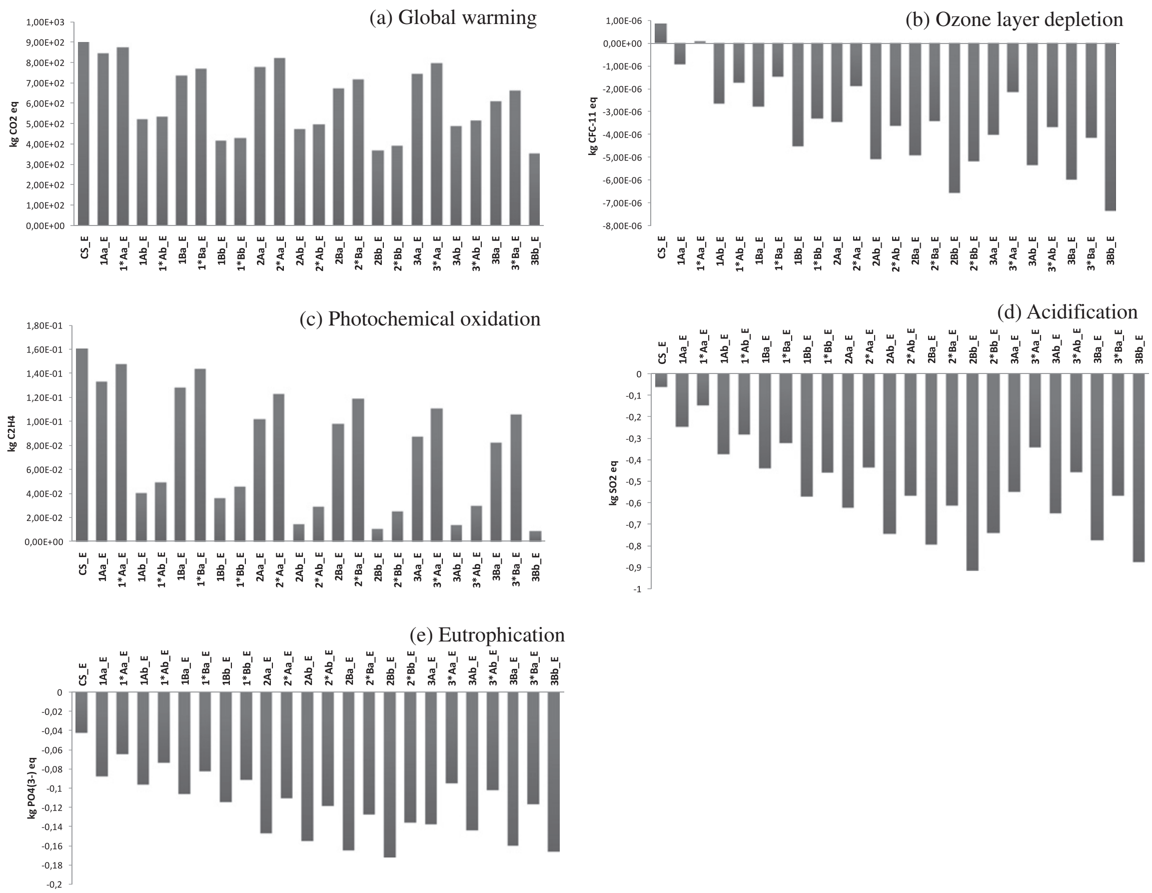

Fig. 8. Net contribution of each scenario to each impact category.

proposed in Table 3 are accomplished, and for the "*optimistic*" scenarios (1Aa, 1Ab, ..., 3Ba, 3Bb), in which the targets are met fully.

Finally, Fig. 8 shows the net contribution that each scenario makes to each impact category.

5. Results and discussion

On analysing the results shown in Fig. 7 concerning the impact of each unit process, it can be concluded that:

– The fuel consumed during the collection, transport and waste sorting stages makes a contribution to the impact in all the categories that were analysed, since there is not any avoided environmental burden attributable to those processes.
– Recycling allows the pollution burden to be avoided for all impact categories, since it avoids the consumption of virgin material according to the substitution rate of 1:1 (see Section 6).
– The contribution made by landfilling depends on whether it is carried out with or without energy recovery. If we look at global warming or photochemical oxidation, it can be seen how incorporating energy recovery into the landfill gives rise to a 50% reduction compared to the impact caused by ordinary landfills.
– Lastly, the slight improvement offered by biogasification compared to composting should also be highlighted.

When it comes to selecting the best scenario, a comparison of the results from the "*optimistic*" and "*pessimistic*" alternatives shows the same hierarchy, since the environmental profiles that are obtained from the analysis of each unit process shown in Fig. 7 are very similar to those obtained in Fig. 8.

On analysing the results displayed in these figures it can be seen that scenarios that combine biogasification and landfill with energy recovery are the best scenarios for all the impact categories. Regarding the collection system, system 3 offers better results for global warming, ozone layer depletion and photochemical oxidation categories (scenarios 3Bb and 3*Bb), while for acidification and eutrophication impact categories, scenarios 2Bb and 2*Bb offers slightly better results than 3Bb and 3*Bb.

The indicators shown in Figs. 7 and 8 were completed with two other indicators for each scenario that quantify the rates of recycling, composting and recovery, as well as the percentage that is sent to the landfill. Table 12 shows the rates of recovery accomplished in each scenario. It must be remembered that the rate of recovery includes any process that gives the waste some value; that is to say, it takes into account recycling, biological treatments and disposal on landfills if this includes energy recovery. In compliance with current legislation, these rates must exceed the values indicated in Table 4 (the scenarios that fail to do so appear shaded in Table 12). Additionally, all these scenarios also comply with all the legal requirements established in the PNIR (2008).

The recycling (%) and the biological treatment (%) are the percentages of material that have been recycled or biologically treated. On the other hand, the recycling rate (%) and the biological treatment rate have been calculated according the following equations:

$$\text{Recycling rate}(\%) = \frac{\text{Recycled material}}{\text{Material available for recycling}}$$

$$\text{Biological treatment rate}(\%) = \frac{\text{Biologically treated material}}{\text{Material available for biological treatment}}$$

Table 12
Rates of recycling, composting and recovery in each scenario.

	Base	50%												100%											
		1 Aa*	1 Ab*	1 Ba*	1 Bb*	2 Aa*	2 Ab*	2 Ba*	2 Bb*	3 Aa*	3 Ab*	3 Ba*	3 Bb*	1Aa	1Ba	1Ab	1Bb	2Aa	2Ba	2Ab	2Bb	3Aa	3Ba	3Ab	3Bb
Recycling rate (%)	31.74	38.29	38.29	38.29	38.29	55.62	55.62	55.62	55.62	53.45	53.45	53.45	53.45	44.86	44.86	44.86	44.86	67.41	67.41	67.41	67.41	64.59	64.59	64.59	64.59
Recovery rate (%)	48.98	51.71	51.71	71.49	71.49	58.42	58.42	78.33	78.33	59.81	59.81	77.09	77.09	54.25	54.25	73.12	73.12	62.98	62.98	82.18	82.18	64.12	64.12	80.19	80.19
Biological treatment rate (%)	59.87	60.19	60.19	60.19	60.19	60.19	60.19	60.19	60.19	63.83	63.83	63.83	63.83	60.19	60.19	60.19	60.19	60.19	60.19	60.19	60.19	63.83	63.83	63.83	63.83
Recycling rate (%)																									
Paper/cardboard	47.26	57.93	57.93	57.93	57.93	65.95	65.95	65.95	65.95	75.17	75.17	75.17	75.17	68.12	68.12	68.12	68.12	78.55	78.55	78.55	78.55	90.80	90.80	90.80	90.80
Plastic	8.68	11.17	11.17	11.17	11.17	35.57	35.57	35.57	35.57	17.96	17.96	17.96	17.96	13.75	13.75	13.75	13.75	46.23	46.23	46.23	46.23	22.84	22.84	22.84	22.84
Glass	18.39	25.74	25.74	25.74	25.74	59.22	59.22	59.22	59.22	56.88	56.88	56.88	56.88	33.09	33.09	33.09	33.09	76.14	76.14	76.14	76.14	73.16	73.16	73.16	73.16
Metal	54.50	54.46	54.46	54.46	54.46	60.67	60.67	60.67	60.67	54.73	54.73	54.73	54.73	56.01	56.01	56.01	56.01	63.31	63.31	63.31	63.31	55.68	55.68	55.68	55.68
Landfill without recovery (%)	54.45	51.91	51.91	33.51	33.51	45.67	45.67	27.16	28.47	44.37	44.37	28.30	29.80	49.54	49.54	32.00	32.00	41.43	41.43	23.58	24.23	40.37	40.37	25.42	25.80
Landfill with recovery (%)	0.00	0.00	0.00	18.40	18.40	0.00	0.00	18.52	17.20	0.00	0.00	16.07	14.57	0.00	0.00	17.55	17.55	0.00	0.00	17.85	17.20	0.00	0.00	14.95	14.57
Recycling (%)	11.42	13.79	13.79	13.79	13.79	20.02	20.02	20.02	20.02	19.24	19.24	19.24	19.24	16.15	16.15	16.15	16.15	24.27	24.27	24.27	24.27	23.25	23.25	23.25	23.25
Biological treatment (%)	34.13	34.31	34.31	34.31	34.31	34.31	34.31	34.31	34.31	36.38	36.38	36.38	36.38	34.31	34.31	34.31	34.31	34.31	34.31	34.31	34.31	36.38	36.38	36.38	36.38

Reducing the fraction of waste that is sent to landfills is another of the aims of the new Spanish legislation regarding solid waste. Fig. 9 shows the percentages of disposal on landfills obtained in each of the scenarios proposed here. Scenarios that include energy recovery at landfills have much lower landfilling percentages, since 55% of the biodegradable waste that is sent to landfills (organic material, compost, paper/cardboard and textiles) is recovered by means of programmes carried out to collect the biogas they produce. Any of the proposed scenarios lead to a reduction in the amount of waste that is sent to sanitary landfills, but the scenarios belonging to models 2 and 3 are the ones that offer the most significant decreases (considering collection targets from Table 3 that are fully accomplished). Scenarios 2Bb and 3Bb display the lowest percentages of landfill without recovery, with reductions of over 50% on the amounts currently sent to landfills.

6. Sensitivity analysis

This section tests how the results are affected by two assumptions made in the inventory model.

The first one analyses how the results are affected by the use of different life cycle inventories for modelling the waste management processes. Particularly, the results obtained from the application of Ecoinvent (2007) database have been compared with those obtained from the application of the integrated waste management (IWM) model from McDougall et al. (2001).

Fig. 10 shows the comparison among results obtained by applying both LCI databases, for *optimistic* scenarios. As concluded in Section 5 and detailed in Table 13, for all impact categories and for both LCI models, scenarios that combine biogasification and landfill with recovery of energy, are the scenarios with the best environmental performance. Therefore, differences appear when the collection model changes. The application of the LCI model from Ecoinvent (2007) for the treatment processes, allow us to select the scenario 2Bb or 3Bb, as the best scenarios depending on the impact category, while the application of the LCI from McDougall et al. (2001) select the scenario 2Bb as the best for all impact categories.

Analysing in detail the LCI data for each treatment, it can be seen that major differences appears in the recycling model. McDougall et al. (2001) give to the recycling treatment and for all impact categories, major burden avoided than Ecoinvent (2007) model. For this reason, scenarios including the collection system 2, that is focused on collecting recyclable fractions and therefore in obtaining higher recycling rates, offers better environmental results when the LCI model from McDougall et al. (2001) is applied. Analogous results can be found for *pessimistic* scenarios.

The second one deals with the influence of the substitution ratio applied in the recycling treatment model. One of the environmental advantages that recycling activities offers us is the replacement of products from virgin material by products from secondary material. This replacement will depend on the changes occur in the inherent properties of the recycled materials. That is to say, if the inherent properties do not change with the recycling process, the secondary material produced displaces the use of the same quantity of virgin material and the substitution ratio is 1:1. This assumption has been considered in the initial recycling inventory model.

On the other hand, when a material undergoes a degradation during the recycling process, like in recycled paper and plastic, the substitution ratio is 1 < 1. The reason is that to replace a certain amount of virgin material, a greater amount of secondary material will be required. According to Rigamonti et al. (2009), paper and plastic represent specific cases because, unlike aluminium, glass and iron, they can be recycled only a limited number of times (see Table 14).

Fig. 11 shows the comparison among the results obtained assuming a substitution ratio 1:1 (black colour) and 1 < 1 (grey

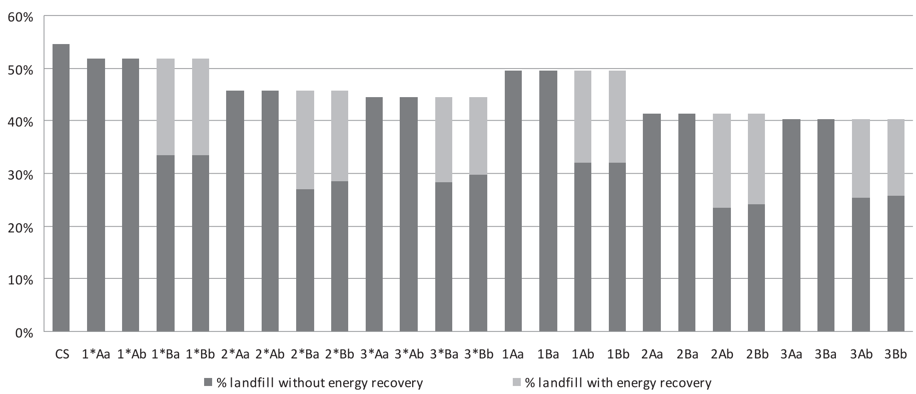

Fig. 9. Percentage of disposal on landfill obtained in each of the scenarios.

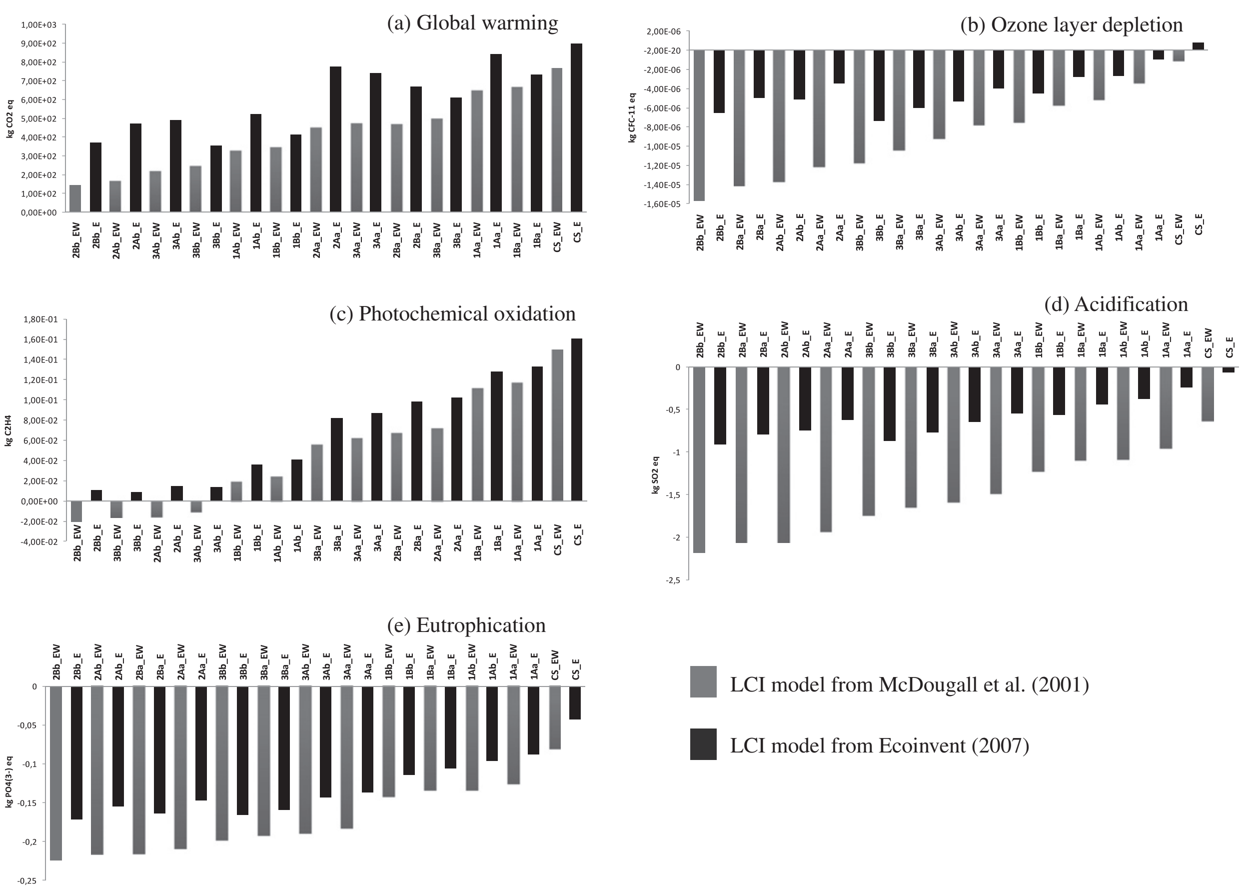

Fig. 10. Comparison of results obtained by applying the life cycle inventory model from Ecoinvent v2 (2007) and McDougall et al. (2001) (*optimistic* scenarios).

Table 13
Scenario with best environmental behaviour for each impact category, and for each assumption in the LCI model.

	LCI model from Ecoinvent (2007)		LCI model from McDougall et al. (2001)
	Substitution ratio 1:1	Substitution ratio 1 < 1	Substitution ratio 1:1
Acidification	2Bb	2Bb	2Bb
Eutrophication	2Bb	2Bb	2Bb
Global warming	3Bb	3Bb	2Bb
Ozone layer depletion	3Bb	3Bb	2Bb
Photochemical oxidation	3Bb	3Bb	2Bb

colour) in the recycling model, for *optimistic* scenarios. As it can be also concluded from Table 14, the substitution ratio of the recycled material vs. the virgin material does not have a significant influence in the results, since the optimum scenario is kept, for all impact categories analysed. Nevertheless, as Table 15 indicates, a substitution ratio 1 < 1 causes a worsening of the environmental indicator. Analogous results can be found for *pessimistic* scenarios.

7. Conclusions

Applying the LCA methodology as a decision support tool in planning new waste management strategies is not a very widespread practice in Spain. This paper has presented an application

Table 14
Substitution ratios of the recycled materials (Rigamonti et al., 2009).

	Substitution ratio
Paper/cardboard	1:0.833
Glass	1:1
Plastic	1:0.81
Ferrous	1:1
Aluminium	1:1

Table 15
Worsen of the environmental indicator when the substitution ratio 1:1 is reduced to those showed in Table 14 (in percentage).

	Percentage (%)
Acidification	20.74
Eutrophication	21.61
Global warming	1.67
Ozone layer depletion	42.27
Photochemical oxidation	23.28

of the LCA methodology to assess the environmental performance of alternative scenarios for the management of municipal solid waste in Castellón de la Plana, Spain. Twenty-four scenarios have been proposed by combining different percentages of selective collection for the paper/cardboard, glass and packaging fractions, different waste collection systems, different treatments for the biodegradable fraction (composting/biogasification) and different types of landfills (without/with energy recovery).

According to the environmental evaluation results obtained from the application of the LCA methodology to each alternative scenario we can conclude:

- Scenarios with biogasification and energy recovery achieve better environmental performances than scenarios without them.
- The substitution ratio does not have any influence in the selection of the optimum scenario because spite of the significant variance reached by the results when we change this ratio, the LCA keeps the hierarchy between the different scenarios for all the impact categories.
- LCI model from McDougall et al. (2001) gives to the recycling treatment, for all impact categories, a great burden avoided. Therefore, using this database the trend is that the optimum scenarios considered are those with bigger recycling rates (collection system 2).
- LCI model from Ecoinvent (2007) gives more importance to biological treatment than recycling treatment, therefore it considers most favorable those scenarios with bigger biological treatment rates. Furthermore, there are not great differences in the burden that recycling avoids depending on the quantities of materials handled. Hence, the trend for results obtained from Ecoinvent database is to point out as optimal those scenarios belonging to the collection system 3.

Although efforts have been made to analyse the environmental behaviour of each alternative so as to be able to choose the most sustainable scenarios, this study needs to be completed with an analysis of the economic and social costs of each alternative. This work will continue along those lines.

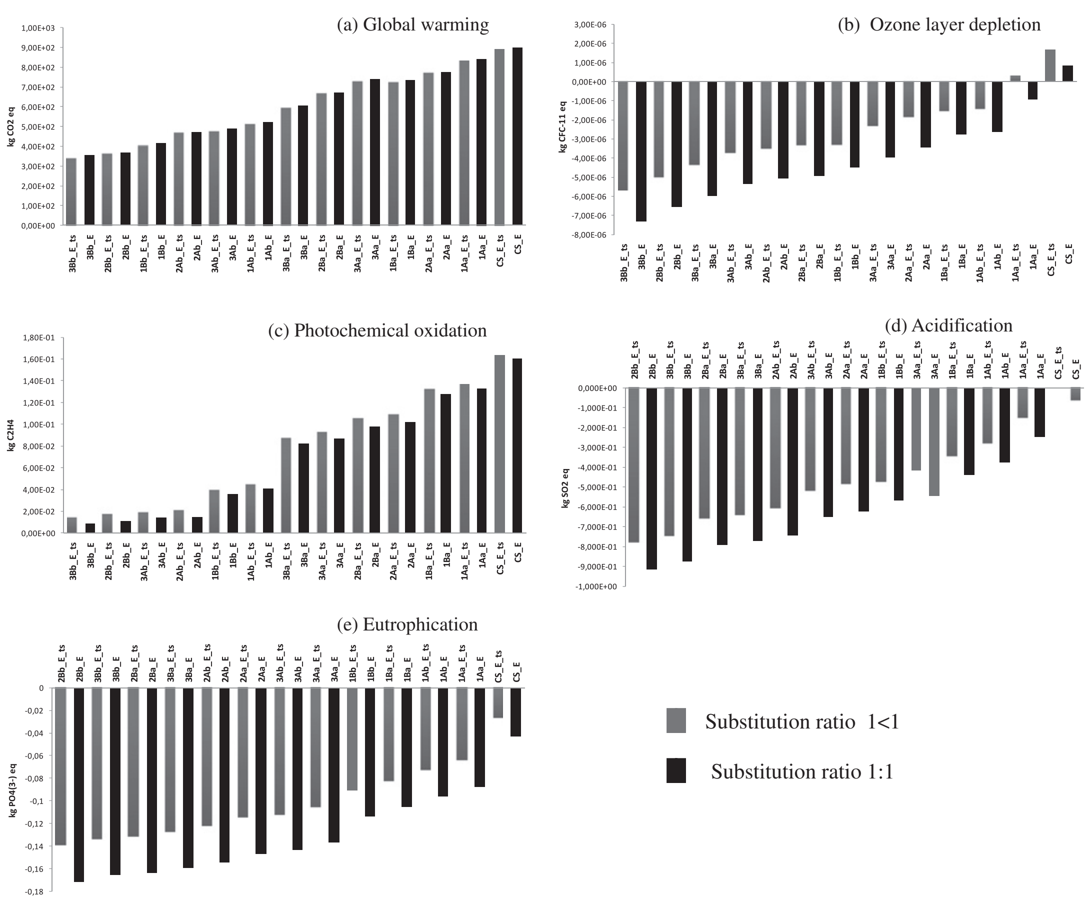

Fig. 11. Comparison of results obtained by modifying the substitution ratio applied in the recycling inventory model (*optimistic* scenarios).

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