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Life cycle assessment of carrier bags and development of a littering indicator

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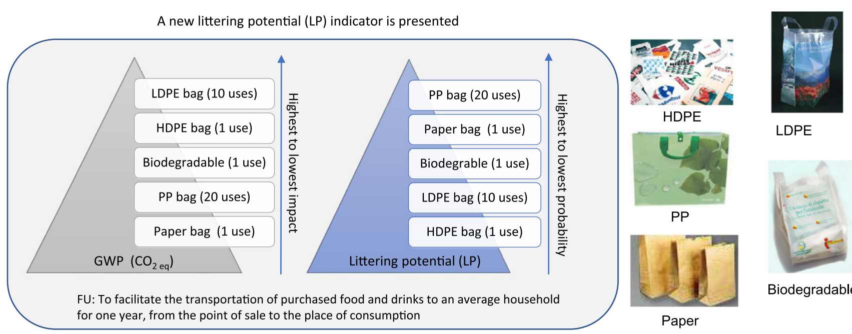
HIGHLIGHTS

- Concerns over uncontrolled plastic waste ending up in marine waters have increased.
- There is no consensus on how to address marine littering impact in LCA.
- A pragmatic littering indicator has introduced based on a carrier bags LCA study.
- The introduced indicator ranks the bags opposite of the LCA study.
- Further research is needed on the introduced littering indicator.

GRAPHICAL ABSTRACT



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ABSTRACT

Increased plastic consumption has resulted in high amounts of plastic waste ending up in the environment. Recently, the European Commission (EC) has identified a list of single-use plastics, including plastic bags, most commonly found in the European beaches. As a response, alternatives for plastic carrier bags have been more of a concern. Many life cycle assessment (LCA) studies have been performed to evaluate the environmental profile of different carrier bags; however, without considering the possibility of contribution to the littering problem. Therefore, in this study, an indicator has been introduced, based on an LCA study of carrier bags which was performed in Spain. The indicator is influenced by parameters such as: number of bags to fulfill the functional unit, weight, surface, fee, and biodegradability. In this paper, a comparative LCA of HDPE, LDPE, PP, paper and biodegradable plastic bags is presented. Following that, a littering indicator is introduced to allow a comparison of the risk of littering of the different carrier bags in marine environment. The results given by the Littering Potential indicator rank the bags oppositely to the results given by the LCA as usual. Further research is needed to refine the model and include additional contributing variables.

1. Introduction

Plastics have been widely used in different kinds of applications, thanks to their high performance and optimal cost. According to Plastics Europe, in 2016, 335 million tons of plastic (including thermoplastics, polyurethanes and other plastics like thermosets, adhesives, coatings

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and sealings) were produced in the world, 60 million tons of those in Europe (PlasticsEurope, 2017). Around 30% of the total annual plastic production is used for packaging purposes (UN Environment, 2018).

The increase in the global plastic production and consumption has led to the accumulation of plastic litter in the environment, especially in the marine waters. Marine littering is defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (UNEP, 2009).

A recent study (Jambeck et al., 2015) showed that, among 275 million tonnes of plastic waste generated in 192 coastal countries in 2010, 4.8 to 12.7 million tonnes of them entered the ocean. It is predicted that this number may double, if no improvements are done in waste management systems. Mismanaged plastic waste is identified as one of the main hotspots for macroplastic littering, especially in the coastal zones (UN Environment, 2018).

Single-use plastics, including plastic bags, have been recently identified as one of the major contributors to marine litter (Steensgaard et al., 2017; Xanthos and Walker, 2017), in addition to other environmental impacts. In the EU, 100 billion plastic bags per year are currently used (EC Environment, 2017). Specifically, LDPE plastic bags are considered as one of the major sources of marine pollution (Steensgaard et al., 2017), as they are the most commonly used ones (Singh and Cooper, 2017).

Marine littering can cause major impacts on ecological, social and economic values. In the case of ecological impacts, the individual organisms like marine mammals, reptiles, birds and fish, may entangle or ingest floating litter. Marine litter can also damage their habitats, like coral reefs, and extend the lifetime of rafting of organisms due to the longer lifetime of plastics. Seafood safety and related human health issues (microplastics), and loss of pleasure due to the environmental degradation (macroplastics) are the major social impacts of marine littering. Finally, marine littering is expected to have some economic impacts on fisheries and tourism activities, and an additional cost due to clean-up activities (UNEP, 2016).

The Medellin declaration on marine litter in life cycle assessment (LCA) and management acknowledged that impacts related to marine debris, plastics and macroplastics are not properly addressed in LCA, despite of the fact that LCA is one of the most commonly used tools for environmental assessment (Sonnemann and Valdivia, 2017). Very recently, in a workshop on marine littering (Strothmann et al., 2018), it was agreed that addressing marine littering within LCA methodology would be meaningful and feasible; however, the methodology needs to be further developed.

A recent review study (Xanthos and Walker, 2017) showed that different measures are being used to reduce plastic marine pollution from plastic bags at legislation level: to ban the sale, to charge customers or to charge the stores which sell them. In Europe, Germany and Denmark pioneered the application of a ban in 1991 and 1994. Following that, since 2002, the other European countries have introduced different levies. In 1994, the Packaging and Packaging Waste Directive 94/62/EC was introduced, specifying reuse targets for plastic packaging. Following that, the European Commission suggested higher recycling targets for plastic packaging: 45% by 2020 and 60% by 2025 (European Commission, 2014). Later, in 2015, the amending Directive 2015/720 was introduced to reduce the consumption of lightweight plastic carrier bags. According to this Directive, members states are required to take measures to reduce the consumption of plastic bags to 40 bags per person annually by 2025 and conduct LCAs of bags (Steensgaard et al., 2017). Although the lightweight plastic bags are identified among the most commonly found items on European beaches, since there is already existing legislation on bags, the Directive on reduction of the impact of certain plastic products on the environment only envisions some measures regarding the extended producer responsibility and raising awareness for lightweight plastic carrier bags (European Commission, 2018).

Paper bags, biodegradable bags, reusable plastic bags, raffia bags and cotton bags are the alternatives to conventional one-use plastic bags. However, they pollute too. Moreover, they may have more impacts than conventional single-use plastic bags, depending on how they are being used. For example, a recent study done by The Danish Environmental Protection Agency (2018) showed that reusable low density polyethylene (LDPE) carrier bags, which are commonly available in Danish supermarkets, provide the lowest impacts for most of the environmental impact categories with regards to production and disposal among the other alternatives (PE, recycled LDPE, polyethylene (PP), recycled polyethylene terephthalate (PET), polyester, biopolymer, paper, cotton and composite bags). The study identified the reuse of LDPE bag as waste bin liner as the preferable end-of-life scenario. Finally, it was recommended that all bags should be reused as many times as possible. Another study, conducted in 2014 in United States, concluded the same: reusable LDPE bags have a better environmental profile than: a) a single-use HDPE bag with 30% recycled content (if reused 6.2 times), and b) a 100% recycled paper bag (if reused 1.7 times). However, the study claims that most of the users do not use LDPE bags a sufficient number of times (Kimmel, 2014). According to Greene (2011), in order to have less greenhouse gas emissions, in addition to be reusable, a plastic bag should contain some recycled plastics. In this study, a PE-based reusable bag with 40% of post-consumer recycled plastic was identified as the one with the lowest impacts. An LCA review study, conducted in 2006 and published in 2011 due to increasing debate on supermarket carrier bags, also identified high density polyethylene (HDPE) carrier bags as the most environmentally friendly option, basically thanks to their lighter weight. As the other studies reviewed, this study also points out the importance of a high number of reuses and its secondary use as waste bin liner (Edwards and Fry, 2011).

Recently, due to the increased debate on environmental impacts of single-use plastics (including plastic bags) and the marine littering problem, impacts of alternative carrier bags are being discussed. Although governments from all over the world performed LCA studies of carrier bags, none of the studies considered the effects of marine littering. Therefore, the aim of this paper is:

- To use a case study on plastic bags carried out in Spain to add some LCA methodological issues to this topic, by introducing a fate model for a marine littering impact category.

The case study to be used is an LCA on supermarket bags conducted in Spain in 2008 by our research group with the aim of providing strategies to Spanish market about the use of supermarket bags (Fullana-i-Palmer and Gazulla, 2008). Although performed 10 years ago, the results were very similar to those of the recent above mentioned Danish study (The Danish Environmental Protection Agency, 2018). Besides, since the main focus of this study is the introduction of marine littering indicator into LCA methodology, but not only to perform LCA of supermarket bags, it seems adequate to use it. In our study, an index for the qualitative comparison of littering risk of different types of bags was developed, following the ISO 14044 clause 4.4.2.2.1: "… However, in some cases, existing impact categories, category indicators or characterization models are not sufficient to fulfill the defined goal and scope of the LCA, and new ones have to be defined." In addition, following the ISO 14044 clause 6, a critical review was performed (ISO, 2006a).

In this paper, the littering model is shown and further developed, taking into account information more recently available, the updated prices of the carrier bags at the supermarket and the new strategies being defined by international organizations, like the proposal for a Directive of the European Parliament and of the Council on the reduction of the impact of certain plastic products on the environment (European Commission, 2018). This will be further developed in Sections 3 and 4.

In Section 2, LCA methodology applied to carrier bags will be presented together with the inventory development. Following that, in Section 3, littering impact indicator will be introduced. Then in Section 4, the results of LCA study and littering indicator will be presented together. Finally in Sections 5 and 6, conclusions and some recommendations for future research will be given.

2. LCA case study on supermarket bags

2.1. Goal and scope

The goal of this LCA study was defined as the identification of environmental impacts of the supermarket bags available in Spain through their life cycle. The following types of bags were investigated:

- Single use high density polyethylene (HDPE) bag
- Reusable low-density polyethylene (LDPE) bag (reusable for the same function)
- Reusable polypropylene (PP) woven bag
- Single use recycled paper bag
- Single use biodegradable (Mater-Bi®) bag

The environmental analysis was carried out following the LCA methodology as defined in ISO 14040 (ISO, 2006b) and ISO 14044 (ISO, 2006a) standards. In this LCA study, GaBi software was used to model the life cycle of different types of carrier bags, to make the inventory and to estimate the related environmental burdens. In addition, LCA results were supported by the definition of a qualitative indicator representing the littering impact of the bags. Although there was no consensus on the identification of the littering impact and knowing that it was considered as a difficult topic, the authors already believed at that time that a study on supermarket bags without taking into account this impact would not have enough credibility. This previous qualitative indicator has been further developed and will be explained in chapter 3.

2.1.1. Function, functional unit and reference flow

The primary function of supermarket bags is to help the customer of the supermarket to transport the purchased goods to the place of consumption. In addition, this function can be completed by the possible reuse of the same bag for the same or another purpose (second function) like collecting the domestic waste. It was known that, when this study was performed, 61% of the population was reusing the supermarket bags to collect domestic waste (Cicloplast, 2004). This second function was only considered for single-use HDPE and biodegradable bags, since LLDPE and PP based bags were broken after several reuse and the properties of paper bags are not suitable for this function.

The characteristics of the five analyzed supermarket bags are given in Table 1. When the study was conducted in 2008, plastic bags were available at the supermarkets in Spain; however, the paper and biodegradable bags were not, and the data about them were obtained from Canada and France, respectively.

The functional unit of the study was identified as: "To facilitate the transportation of purchased food and drinks to an average household for one year, from the point of sale to the place of consumption".

According to the Panel of Food Consumption (MAPA, 2007), based on a sample of 8000 households, 644.1 kg of food and beverages were being consumed per person per year in Spain. Based on the data provided by the Panel, each household was formed by 2.71 persons and the yearly shopping was being done in 17 monthly purchases in a year. From this data, it was estimated that each year 1745.51 kg (644.1 × 2.71) of food and beverages per household were acquired and 204 visits (17 × 12) were made to supermarkets, hypermarkets, stores, markets, etc. And in each visit, 8.56 kg (1745.51/204) food and beverage was purchased. Assuming the average density of the purchased products was 0.45 kg/L,[1] it was calculated that each purchase has the volume of 19.01 L.

For the determination of the corresponding reference flows of each bag, transportation capacity of the bags (in terms of weight and volume) and the number of reuses were taken into account. The following Table 2 shows the results obtained when calculating the number of bags needed for 204 annual purchases of products. For the calculation, both mass and volume were considered and the highest was taken to calculate the reference flow. As each purchase weights 8.56 kg/19.01 L, considering the maximum transportable weight (6 kg)[2] recommended by the Health and Safety National Institute (INSHT, 1998) and the volumetric capacity of each bag (considering an 85% use), the number of bags required for each purchase was defined for each bag. Later, to be able to calculate the number of bags required during a year (in which 204 visits to supermarkets take place), the number of reuses per each bag was

Table 1
Characteristics of the analyzed supermarket bags.

High density polyethylene bag (HDPE single use)	
Weight (g)	7.62
Dimensions (cm)	25 × 40
Volume (L)	13.75
Maximum load (kg)	9.25
Thickness (μm)	23.44
Reuse	Single use
Composition	10% recycled
Source	Samples from Spanish producers
Low density polyethylene bag (LDPE 10 uses)	
Weight (g)	43.2
Dimensions (cm)	46.5 × 45.5
Volume (L)	29.3
Maximum load (kg)	–
Thickness (μm)	–
Reuse	Reusable
Composition	100% virgin
Source	A sample bag from Carrefour
Polypropylene woven bag (PP 20 uses)	
Weight (g)	226
Dimensions (cm)	37 × 51.5
Volume (L)	43.3
Maximum load (kg)	–
Thickness (μm)	–
Reuse	Reusable
Composition	100% virgin PP, 100% recycled paper (carton layer)
Source	A sample bag from Carrefour
Paper bag (single use)	
Weight (g)	55
Dimensions (cm)	29.9 × 43 × 17.5
Volume (L)	22.5
Maximum load (kg)	–
Thickness (μm)	–
Reuse	Single use
Composition	100% recycled
Source	Sample bags from IGA and METRO (Canada)
Biodegradable (Mater-Bi®) bag (single use)	
Weight (g)	12
Dimensions (cm)	26.7 × 36.5
Volume (L)	14
Maximum load (kg)	–
Thickness (μm)	–
Reuse	Single use
Composition:	50% starch, 50% polycaprolactone
Source	A sample bag from Ecolobag (France)

[1] This value is calculated from the following information: a transport container of 88 m3 capacity and containing different types of product to be sold in a supermarket, weights 40 t if it is fully loaded (Fullana-i-Palmer and Gazulla, 2008)

[2] Although HDPE bags can easily carry 10 kg.

Table 2
Reference flows corresponding to the defined functional unit.

Material	Volume	Used volume	Number of bags per purchase		Number of uses in purchasing	Number of bags per functional unit (204 purchases in a year)
			Based on volume (19.01 L)	Based on mass (8.56 kg)		
HDPE	13.75	11.7	2	**2**	1	408
LDPE	29.3	24.9	1	**2**	1	408
					5	82
					10	41
PP	43.3	26.8	1	**2**	1	408
					10	41
					20	21
Paper	22.5	19.12	1	**2**	1	408
						Biodegradable
14	11.90	2	**2**	1	408	

considered. For simplification purposes, the results were presented for 10 reuses for LDPE bags and 20 reuses for PP bags.

2.1.2. System boundaries

In this study, the total life cycle of the bags, including extraction of raw materials, transportation, production, distribution to the consumers and end-of-life, was considered (Fig. 1).

However, the following elements were decided to be kept outside the system boundary:

- The production of machinery and industrial equipment. They were not considered due to the difficulty of data gathering and because it was commonly believed that their allocated impacts are negligible compared to the other elements in the system.
- Impacts from the use phase. They are negligible. They are caused by the transportation of the bag from supermarket to the consumer's home, which is much shorter than the other transportation processes involved in the life cycle.
- Recycling of waste. In this study, for the allocation of impacts, the authors accepted to use the rule known as "cut-off", which considers that the recycling of waste belongs to the second life of the material. For this reason, recycling of waste was not considered in the system boundary (explained in Section 2.1.4 in detail); however, the recycling of the incoming secondary material was considered indeed.

2.1.3. Multifunctionality

When the study was conducted, 61% of the Spanish population was reusing the supermarket bags as waste bin liners (Cicloplast, 2004), which brings a new function to the system.

According to Baumann and Tillman (2004), system expansion is one of the methods to be used when a second function is provided by the product, the system is then credited with the environmental load of an avoided production. In this case, this is the production of waste bin liners. Therefore, also following the recommendation of ISO Standards, in this study, allocation of impacts is avoided by applying system expansion and the burdens of waste bin liner production are subtracted from the system (Fig. 2).

2.1.4. Allocation

In this study, as the second life of the bags material was unknown in open-loop recycling, for the end-of-life (EoL) allocation, the so-called "cut-off approach", which assigns the recycling process to the next product cycle (Baumann and Tillman, 2004), was used.

Therefore, the burdens from the previous processes regarding the preparation of recycled material (transportation to the material recovery plant, separation and classification of recyclable materials, transportation to the recycling plant, washing and cutting to get recycled granulates) were allocated to the upstream system, while the credits from the EoL recycling of the bags were allocated to the

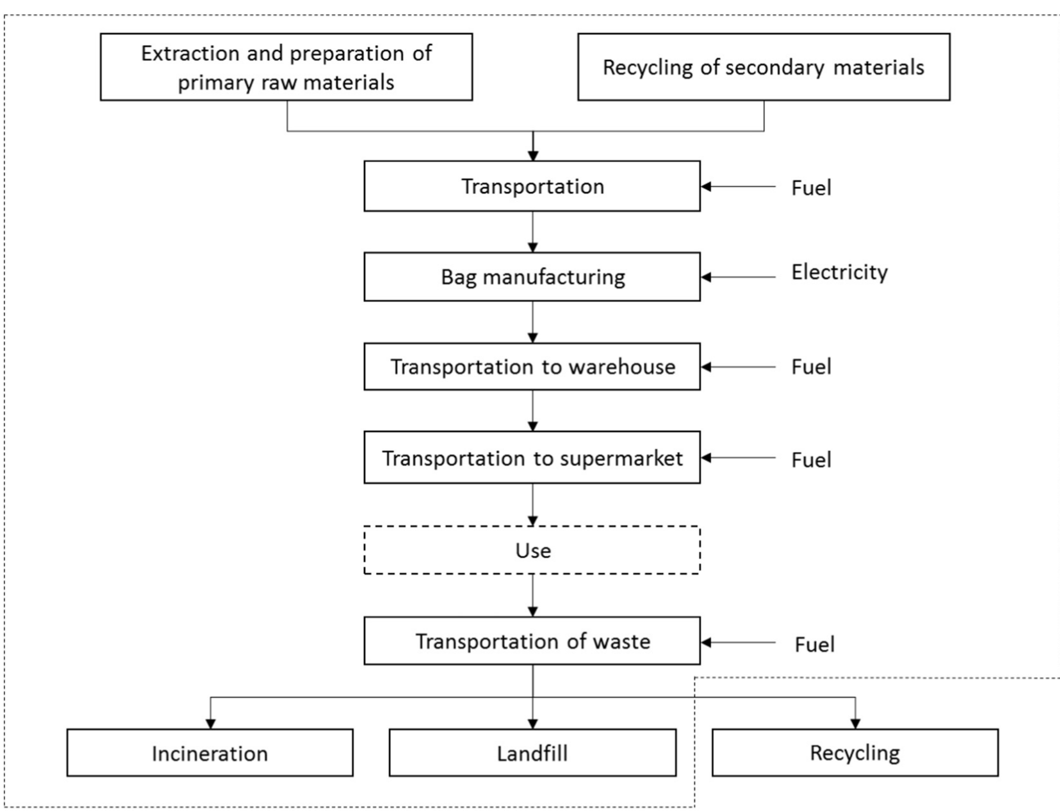


Fig. 1. System boundary.

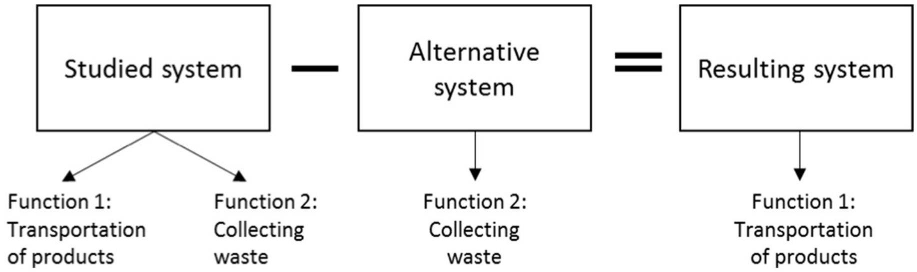


Fig. 2. System expansion.

downstream system. That's the reason why, in the case of recycling, the system boundary was cut at the waste containers.

On the other hand, in the case of incineration and landfilling scenarios, waste management systems include energy recovery. In both scenarios, system expansion was used. The national energy profile of electricity production was not considered representative of the marginal changes that may occur in the demand. It is fundamental to correctly choose the technology displaced by the system, that is, the marginal technology of electricity production in Spain at that moment, which was identified as thermoelectric production from fuel/gas (Fullana-i-Palmer and Gazulla, 2008).

In the same way, within the production of paper, electricity and thermal energy are produced. Again, to avoid allocation, system expansion was performed as explained above.

2.1.5. Impact categories

The following environmental impact categories were decided to be used in the study among the ones recommended by a relevant operational guide to the ISO Standards at that time (Guinee et al., 2001):

- Abiotic resource depletion (ADP)
- Acidification potential (AP)
- Global warming potential (GWP)
- Eutrophication potential (EP)
- Photochemical ozone creation potential (POCP)

In addition, the following indicators were included in the analysis, as well:

- Primary energy consumption (PE)
- Water consumption
- Risk due to the abandonment of the waste bags on marine environment (explained in chapter 3)

2.1.6. Hypothesis and limitations of LCA

- It was a common behavior for the consumers not to fill the bags at their 100% capacity, especially if they were for free. Thus, it was assumed that the supermarket bags were filled at 85% of their capacity, both in terms of weight and volume.
- A theoretical number of uses was established for reusable bags, which was greater in the case of polypropylene (more resistant) than in that of LDPE.
- According to Cicloplast (2004), 61% of the population were using the supermarket bags to collect domestic waste. It was considered that only HDPE and biodegradable bags were reused for this purpose, and at a maximum of 85% of its volume. This second function involves the proportional substitution of waste bin liners.
- In the case of PP bags, no environmental data was found on the production of braided PP. This material was assimilated to PP sheet. This was undoubtedly a hypothesis that benefits the results of the PP bag.
- In the case of the paper bag, it was considered that it was made of 100% recycled material based on.
- The location of bag producers, in the case of HDPE and LDPE was Spain, in the case of PP was China, and in the case of the biodegradable bag was Italy.
- For transportation in Europe, a Euro 3 truck with 17.3 tons of maximum load was used. For the distances above 700 km, it was assumed that the truck returned loaded with other products, thus it was out of the system. On the other hand, for the distances shorter than 700 km, a return trip was also included.
- For the end-of-life modelling, a generic Spanish waste management scenario, which includes recycling, incineration with energy recovery and landfilling with energy recovery from biogas production, was considered. Table 3 shows the percentage of different types of waste bags being treated through different options. In the case of bags having a secondary function (being used as waste bin liners), this waste management scenario applies after the second function. Thus, for the 39% of the bags, it applies after the first use and, for 61% after the second use, as waste bin liners.
- For the transportation of the waste generated, three assumptions were taken: 1) all treatment plants were located at the same distance (50 km); 2) the packaging waste (wooden pallets and cardboard boxes) was transported directly from the supermarket to the corresponding treatment plant; and 3) the waste bags were transported by the consumer, on foot, to the city waste container.
- For the calculation of environmental loads from incineration and landfill scenarios, Ecoinvent database was used. In both cases, energy recovery was done through the gas or biogas produced from the incineration or decomposition of waste.
- Finally, it should be noted that, since no specific waste management models were found for the biodegradable material, the following hypotheses were adopted in terms of its behavior: the biodegradable material would behave like plastic in the case of energy recovery and like paper in the case of dumping (except for the different calorific value in both cases).

Table 3
End-of-life treatment of carrier bags (Fullana-i-Palmer and Gazulla, 2008).

Waste type	Recycling (%)	Incineration with energy recovery (%)	Landfill with energy recovery from biogas production (%)
HDPE bag (1 use)	10.8	44.0	45.2
LDPE bag (10 uses)	19.9	13.7	66.4
PP bag (20 uses)			
Paper bag (1 use)	57.3	4.4	38.3
Biodegradable bag (1 use)	0	17.1	82.9
Wooden pallet	41.7	1.3	57.0
Cardboard boxes	57.3	4.4	38.3
Reused bags as waste bin liners	13.5	4.3	82.2

2.2. Inventory development

The data used in this study is foreground whenever possible or were collected from the GaBi database or literature depending on the availability of the data. The inventories of five carrier bags are presented in Table 4.

For the raw materials, data regarding the production of HDPE, LDPE and PP granulates were taken from Gabi database 2005, while the paper production and granulate production data for biodegradable bags were provided by the producers. The composition of pigments, adhesives and dyes were gathered from the producers and modelled using the Gabi database.

In addition to the assumptions given in Section 2.1 regarding transportation, the distances considered in the study are presented in Table 5.

The environmental impact associated with the manufacture of the bags was mainly due to the consumption of energy. The data on energy consumption during extrusion was gathered from the collaborating companies.

For the reutilization of the bags as waste bin liners, in the case of HDPE bags, it was assumed that for each 3.9 bags reused, the production of one garbage bag was avoided. The calculation was done as follows for the reference flow: 408 (number of bags) $*$ 0.61 (reuse factor) $*$ 13.75 L (volume) $*$ 0.85 (fullness rate) = 2908.78 L. Assuming that each garbage bag has volume of 27.5 L, in total the production of 105 garbage bags was avoided. In the case of biodegradable bags, this number was found as 107 bags, doing the following calculations: 408 (number of bags) $*$ 0.61 (reuse factor) $*$ 14 L (volume) $*$ 0.85 (fullness rate) = 2961.67 L and assuming the same capacity as above. The reused bags have the end-of-life scenarios presented in Table 3.

3. A proposal for a littering LCIA category

In this section, a method for calculation of the littering indicator (land and marine) to identify the risk from abandoned bags on the environment is described. The model is proposed to be only used with comparison purposes. It is a simple approach to detect the bags that may have a greater risk of being abandoned and causing damage to the environment (impact on ecosystem and/or visual impact).

The first proposal of the littering indicator was done in 2008 as a part of the project of LCA of plastic bags in Spain (Fullana-i-Palmer and Gazulla, 2008) motivated by the critical review of the LCA study. In the present paper, that model has been revised and further developed also considering the latest proposal for European Legislation on reduction of plastics on the environment (European Commission, 2018).

It is assumed that littering is proportional: a) to the quantity of bags required for the same function (stated in LCA study); b) to the bags released to the environment c) to the dispersion of the bags on the environment and d) to the environmental persistence of the bag's material.

Therefore, the characterization model is formed based on these four parameters (which are not usual LCI results), and their combination delivers the category indicator. The choice of the influencing parameters is based on the following reasons:

- P1- Quantity of bags. It refers to the number of bags which are required to meet the functional unit of the LCA study (the reference flow for each system being compared). It depends on the number of bags used and the surface area of one bag.
- P2 - Environmental release. It represents the probability of the bag being abandoned in the environment. For this parameter, the price of the bags at the supermarket was taken as the decisive contributor. For example, in the case of low-charge bags, the probability of abandonment by the consumer is expected to be higher than those of higher payment.
- P3 - Environmental dispersion. It is the bag floatability and the probability of flying out. For this parameter, the weight of the bag is the defining contributor. The lighter the bag, the higher the probability of flying.
- P4 - Environmental persistence. It is the persistence of the bag in the environment; in other words, for how long it will remain there after it is abandoned. For this parameter, biodegradability of the bag's material is chosen as defining measure.

As said, the model was formed based on the four parameters above, which combined deliver the category indicator. The probability of the bags becoming litter is assumed to be directly proportional to the number of bags required, while it is reversely proportional to the price, weight and biodegradability. Therefore, the littering potential index was defined as follows:

$$LP = \frac{P1^{f1}}{P2^{f2} x\, P3^{f3} x P4^{f4}}$$

where:

LP = Indicator for assessing the littering potential on the environment

P1 = Quantity of residual bags

P2 = Environmental release

Table 4
Inventory per functional unit for the different carrier bags.

Raw materials	HDPE bag (1 use)	LDPE bag (10 uses)	PP bag (20 uses)	Paper bag (1 use)	Biodegradable bag (1 use)
Virgin HDPE (g)	4.998				
Recycled HDPE (g)	0.762				
LDPE (g)		41.66			
PP (g)			135.6		
Pigments (g)	0.205	1.3	0.6		
Adhesives (g)	0.0054				
Dye (g)	1.65	0.24	1.8	2.1	0.2
Recycled paper (g)			88	49.7	
Glue (g)				3.2	
Biodegradable (g)					12
Packaging materials					
LDPE (g)	0.039	0.65	0.85		0.061
Cardboard (box) (g)	0.25	1.46	7.5	1.83	0.4
Wood (pallet) (g)	0.061	0.35	9.04	0.44	0.096
Energy consumption					
Electricity (kWh)	0.0044	0.020		0.0114	0.0055
End-of-life					
Landfill (g)	7.26	28.68	150	21.05	11.4
Incineration (g)	3.55	5.92	3	2.4	0.6
Recycling (g)	1.45	8.60	45	31.5	

Table 5
Transport distances.

	HDPE, LDPE, Paper bags (km)	PP bag (km)	Paper bag (km)	Biodegradable bag (km)
Transportation of raw materials				
HDPE	1500			
Recycled HDPE	400			
LDPE	1500			
PP		1500		
Pigments	530	1500		
Adhesives	530			
Dye	530	1500	530	500
Recycled paper		1500	750	
Biodegradable				500
Transportation of packaging materials				
Cardboard (box)	200			
Wood (pallet)	200			
Transportation to supermarket	260	1773 (650 km truck in China + 16,763 km ship + 360 km truck in Spain)	260	1500
Transportation to the treatment plant (end-of-life)	50	50	50	50

P3 = Environmental dispersion
P4 = Environmental persistence
f1, f2, f3, f4 = Weighting factors (all equal to 1, until further research inputs otherwise)
Where values are $0 < P1, P2, P3, P4 < 1$.
The dimensionless parameters are calculated as follows:

$$P1 = \frac{(n\ x\ S)}{(n\ x\ S)_{max}}$$

where:
n: Number of the bags corresponding to the functional unit
S: Surface area of one side of the bag (m^2)
$(n\ x\ S)_{max}$: Maximum result among the bags

- P2 can be calculated as;

$$P2 = \frac{p}{p\ \ max}$$

where:

p: price of the bag (Euro)
P_{max}: Maximum price among the bags (Euro)

- P3 can be calculated as;

$$P3 = \frac{w}{w\ \ max}$$

where:

w: weight of the bag (g)
w_{max}: Maximum weight among the bags (g)

- P4 can be calculated as;

$$P4 = \frac{d}{d_{max}}$$

where:

d: environmental degradation rate of the material used in the bag (1/day)

d_{max}: maximum environmental degradation rate among the bags (1/day)

The Littering Potential (LP) must be a number, so that results of different types of bags can be compared to each other. In the same way, the different influencing parameters and the mathematical operations combining them to get the category indicator must be numerical as well. The rules which were applied when defining the index are explained below:

- All influencing parameters must be dimensionless for them to be combined. For that reason, while calculating each parameter (P1, P2, P3 and P4), each value is divided by the maximum result found.
- Therefore, no absolute impacts are pursued, but relative to one another. The introduced formula does not predict the impact on the final receivers, but it defines relative expressions.
- Weighting factors (f1, f2, f3 and f4) exist to be able to vary the importance assigned to each of the parameters considered in the formula. In this study, an equal importance has been assumed for all influencing parameters, as there is no proper research to assess these values so far.

As already said, LP is directly proportional to the number of bags required for the functional unit, the more of bags in use, the higher the probability of a littering problem. Price, weight and biodegradability are parameters with assumed reverse proportionality to LP. A bag with a higher price would have lower probability of being thrown away. In a similar way, a bag with lighter weight would have highest probability of flying away and contributing to littering problem. Finally, if a bag has higher biodegradability, it will disappear in a shorter time, thus having lower probability of littering.

In this study, these four parameters were considered while developing the indicator, however, there may be other relevant parameters to be included in the indicator to calculate LP. More discussion on potential additional parameters to include will be provided in Section 6.

4. Results and discussion

The results of the LCA study of the bags are presented in Table 6 for each impact category investigated. LDPE and HDPE bags present better environmental results in most of the environmental impact categories according to the scenarios considered for Spain. They present equal impacts for EP and POCP and very similar results for AP (10% difference). On the other hand, LDPE bags present the best result in GWP, while biodegradable bags have the lowest impact in ADP and PE total. At the

Table 6
LCA results of supermarket bags per functional unit.

Impact	Unit	Bag type				
		HDPE (1 use)	LDPE (10 uses)	PP (20 uses)	Paper (1 use)	Biodegradable (1 use)
ADP	kg Sb eq.	9.67E−02	7.76E−02	1.54E−01	1.68E−01	5.34E−02
AP	kg SO_2 eq.	2.89E−02	3.18E−02	2.01E−01	7.55E−02	4.84E−02
GWP	kg CO_2 eq	9.32E+00	7.82E+00	2.42E+01	2.95E+01	1.45E+01
EP	kg PO_4 eq.	2.90E−03	3.00E−03	1.36E−02	2.68E−02	1.12E−02
POCP	kg C_2H_4 eq.	4.70E−03	4.90E−03	1.55E−02	9.60E−03	5.40E−03
PE non-renewables	MJ	2.26E+02	1.89E+02	3.55E+02	3.47E+02	1.35E+02
PE renewables	MJ	1.13E+01	3.82E+00	7.21E+00	4.43E+01	1.64E+00
Water	kg	1.35E+01	1.56E+01	2.18E+01	1.30E+02	2.93E+02

other extreme, PP bags and paper bags are those that generally have higher impact values.

Littering potential results calculated by using the LP impact indicator, which was introduced in Section 3, are presented in Table 7. For the calculation of the indicator scores, data for each parameter was taken from the original LCA study (Fullana-i-Palmer and Gazulla, 2008), except for the price as there had been major policy changes (introduction of mandatory fees). According to the market research done, the average fee for PP bags was identified as 0.50 euro in Spanish supermarkets. HDPE, LDPE and biodegradable bags had a fee of 0.10 euro. For paper bags, two different fees were available in the supermarkets, 0.10 and 0.15 euro. The average of them was taken as 0.13 euro. In the case of a bag being free of charge, P2 would equal to 0, which would make the indicator incalculable. To avoid this, it is recommended to use 0.01 euro instead of 0.

For the calculation of P4, the study developed by California State University Chico Research Foundation (2007), in which various laboratory tests were carried out following the protocols of ASTM D5338-98 (ASTM International, 2003), was used for the estimation of environmental degradation rates of paper, plastic (PP) and biodegradable materials. In the case of the PP bag, having no data, the same rate as for PE bags was assumed, and for the biodegradable bag the rate corresponding to "biodegradable materials based on corn" was used.

In Fig. 3, the results of LCA of the bags are presented normalized to HDPE bags, as being one of the options with lowest environmental impacts, together with results of the LP calculated in Table 7.

As it can be observed in Fig. 3, the differences between the impacts of different types of bags can be remarkable for a single impact category. For example, in the case of water consumption, biodegradable bags have 27.1 times more consumption than the HDPE bags, while in terms of EP, paper bags have 9.2 times that the impact of HDPE.

However, it is important to note that, if smaller number of reuses for LDPE and PP bags were considered, more bags would be needed to fulfill the functional unit and the results would be worse for them.

On the other hand, the LP indicator calculated for comparison purposes showed that single-use HDPE bags have the highest risk of littering, mainly as a result of being single-use, lightweight, cheap and non-biodegradable. They are followed by the LDPE bags. Since LDPE bags have higher number of reuses and higher weight, their risk of littering was estimated to be less than HDPE, but still higher than PP, paper and biodegradable bags. Although paper and biodegradable bags are single-use, thanks to their much higher biodegradability, they come out with the low scores for the LP indicator gave small values for them. The best results were offered by the PP bag, because of the highest weight and price compared to the other options, which makes it unlikely to be abandoned and dispersed on the environment.

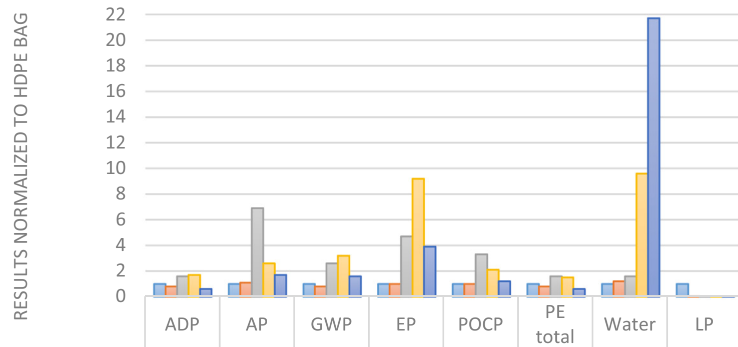
It was interesting to find out that LP calculated resulted in nearly the opposite ranking of the conventional LCIA results. The conventional LCIA results gave preference to LDPE and HDPE bags, while the LP indicator identified these types of bags as having the highest probability of contributing to marine littering problem (Fig. 4).

While calculating the indicator, remarkable variations between the parameters of each bag were observed (Table 7). For example, while calculating P1 (quantity of bags), although the surface area of the bags did not differ much, the number of bags required for the defined functional unit varied significantly depending on the number of reuses. In the case of P2 (environmental release), which considers the price, PP bags got the highest value compared to the others, as it has a relatively higher price than others. The weight of the bags also showed a considerable variety while estimating P3 (environmental dispersion). For example, a PP bag weights 226 g while a HDPE bag weights 7.6 g. Finally, when calculating P4 (environmental persistency), biodegradability of materials showed large differences between plastic bags (HDPE, LDPE, PP), and paper and biodegradable bags.

If the variation between the parameter values for one specific parameter is high, this translates into a wide variation in the final index calculated. For example, in the case of P2, if one of the bags has a much higher price than the others (PP bag), for the calculation of the final index, it is divided by 1 and final result is not affected by this parameter. On the other hand, for other options which have relatively very lower price, the final index is divided by something very small, close to 0, and the indicator easily gets a very high value. The influence of a parameter on the final LP index may be reduced by assigned values lower than one to the corresponding weighting factors (f) (representing the relevance of each parameter to the littering risk), and this represents an important future research priority for the method.

Table 7
Results of the introduced littering indicator for the bags.

Parameter	HDPE bag (1 use)	LDPE bag (10 uses)	PP bag (20 uses)	Paper bag (1 use)	Biodegradable bag (1 use)
P1 – Quantity of bags	**0.77**	**0.16**	**0.08**	**1.00**	**0.77**
n	408.00	41.00	21.00	408.00	408.00
S (m^2)	0.10	0.21	0.19	0.13	0.10
n x S	40.80	8.61	3.99	53.04	40.80
P2 – Environmental release	**0.20**	**0.20**	**1.00**	**0.26**	**0.20**
p (Euro)	0.10	0.10	0.50	0.13	0.10
P3 – Environmental dispersion	**0.03**	**0.19**	**1.00**	**0.24**	**0.05**
w (g)	7.60	43.20	226	55.00	12
P4 – Environmental persistency	**0.01**	**0.01**	**0.01**	**1.00**	**0.99**
d (1/day)	0.1	0.1	0.1	13.60	13.40
LP (P1/(P2*P3*P4))	**15,555**	**577**	**10.2**	**15.8**	**73.5**



	ADP	AP	GWP	EP	POCP	PE total	Water	LP
HDPE bag (1 use)	1	1	1	1	1	1	1	1
LDPE bag (10 uses)	0.8	1.1	0.8	1	1	0.8	1.2	0.0371
PP bag (20 uses)	1.6	6.9	2.6	4.7	3.3	1.6	1.6	0.0007
Paper bag (1 use)	1.7	2.6	3.2	9.2	2.1	1.5	9.6	0.001
Biodegradable bag (1 use)	0.6	1.7	1.6	3.9	1.2	0.6	21.7	0.0047

Fig. 3. Comparison of the LCIA results of different bags (normalized to the HDPE bag).

As the indicator does not calculate an absolute littering impact, but estimates relative risk between different bag options, the results can be interpreted as the probability of the bags contributing to littering problem in the environment. For example, according to the results shown in Table 7, one should expect to find 30 times more HDPE bags than LDPE bags represented in the environmental littering or, for each 1000 units of HDPE bags found as littering only 7 units of PP bags should be found littered.

5. Conclusions

This study presents the results of an LCA of carrier bags, which was conducted in Spain in 2008, together with the results of a new defined indicator to assess their risk of marine littering.

Considering the usual impact categories, the results of the study showed that multiple-use LDPE bags present the best environmental results in all impact categories, if they were used at least 10 times. Single-use HDPE bags, with a second use as waste bin liners, were the second best. Contrarily, multiple-use PP and single-use paper bags had the highest environmental impacts. The impact of the reusable bags (LDPE and PP) clearly depends on the number of uses and on the other hand, the reuse of single-use bags (HDPE and biodegradable ones) to collect garbage represented an important saving of environmental impacts.

However, a feeling of incompleteness arises if no impact assessment on littering is performed. The littering indicator introduced in this study is a pragmatic approach to model the relative littering impacts of carrier bags which are available at supermarkets. It calculates the relative risk between the different options, instead of assigning a final impact. It is a product specific indicator, since it calculates a value based on the properties of the bag. In the end, the bag with the lowest value gets the lowest probability of littering compared to the others.

For the calculation of the indicator, the presented formula considers the number of bags required to meet the functional unit of the study, surface area, weight, price and biodegradability of the materials applied to the bag. Among the bags within the LCA study, PP bags were the ones with lower risk of abandonment on the environment, while HDPE bags had the highest value. It was interesting to find out that, while the risk of littering for PP and paper bags was found to be very low, they had the highest impacts in the conventional LCIA categories, while the opposite was observed for the polyethylene bags. Thus, if policy making is focused on littering impacts, the decision to support a type of bag and ban another would conflict with science based and internationally agreed LCA results.

Since the cleaning of environment from plastic is a difficult process, this method on littering assessment may support a prevention-based solution in the life cycle of the bags. It may help

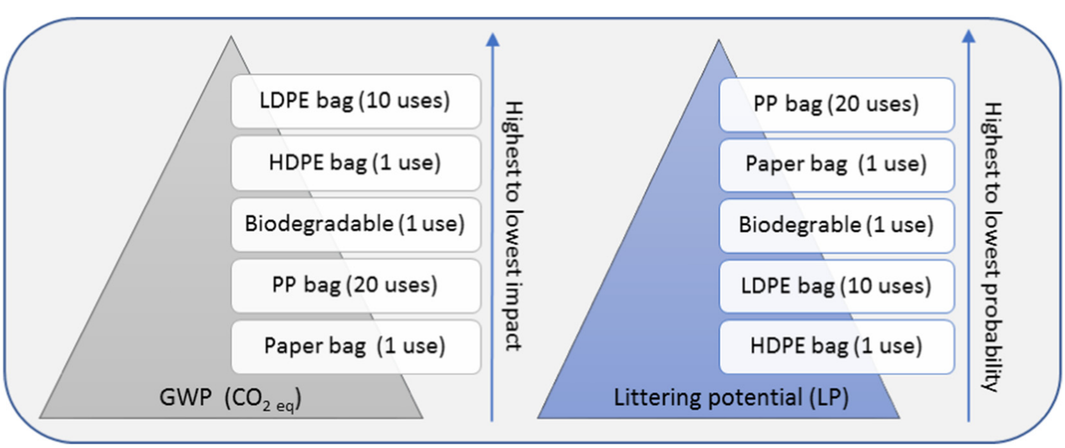


Fig. 4. Comparison of global warming potential (GWP) with littering potential (LP) of the bags.

to detect the one among the options with higher risk to end up in the environment.

6. Further research

In this study, the proposed littering indicator is based on the characteristics of the carrier bags. Therefore, this indicator has to be extended to other types of packaging as well.

As a further step, the inclusion of other physical and social parameters can be useful. For example, a plastic bag thrown away near a shoreline would have higher probability of contributing to marine littering than the one thrown kilometer away far from the marine environment. In addition, the efficiency of the regional waste management system in place would also affect the littering risk. In places where a return-and-deposit system is applied, the probability of littering is expected to be somehow smaller than in those without, but it is uncertain how much this influences. Therefore, some questions still remain unsolved, like the relevance to include additional parameters in the LP indicator, the most adequate weighting factors for the constituting parameters, etc. Further development of the proposed expression for LP may be guided by an empirically based evaluation, comparing the ratio between calculated littering potentials for different plastic bags with the observed occurrence of these plastic bags in the environment. Such studies may be performed in different geographical regions with difference prices structures, waste treatment systems, distances to the coast etc.

Finally, for the calculation of P4, the biodegradability of plastics under controlled composting condition was used, which may not represent the reality, e.g. in marine environments. Up to now, there is no standard defined to determine the biodegradability of floating plastics in the marine environment and due to the unavailability of data, biodegradability in composting was used for the calculation of the parameter.

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