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Life cycle assessment of mechanical recycling of post-consumer polyethylene flexible films based on a real case in Spain

M.A. Martín-Lara[a,*], J.A. Moreno[a], G. Garcia-Garcia[b], S. Arjandas[c], M. Calero[a]

[a] Department of Chemical Engineering Faculty of Sciences University of Granada, Avda. Fuentenueva, s/n, 18071, Granada, Spain
[b] Department of Chemical and Biological Engineering, The University of Sheffield, Sir Robert Hadfield Building, S1 3JD, Sheffield, UK
[c] Department of Waste Treatment, FCC Environment Services, Granada, Spain

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ABSTRACT

Mechanical recycling of plastic waste is a common practice in industry and is an environmental solution to the problem of plastics disposal. In this article, a case study of mechanical recycling of post-consumer polyethylene flexible films in Granada (Spain) was analyzed from an environmental point of view by the Life-Cycle Assessment methodology. The industrial process is divided into four large areas of operation: sorting, washing, extrusion and wastewater treatment. The results show that the washing area has the largest environmental impacts, mostly due to the electricity consumption, followed by sorting. Also, the overall mechanical recycling process causes damage, mainly, on human health, which dominates over ecosystems and resources with 93.4% of the total impact of the process. Two different scenarios have also been considered for the generated waste, and they critically affect the overall environmental performance of the entire process. The first scenario considers the impacts of the landfill disposal of the humid organic matter generated and the losses of PE. In this scenario, all the CH_4 resulting from the anaerobic degradation of organic matter was emitted into the atmosphere. In this case, human health impact was high. In the second end-of-life scenario, all the CH_4 generated would be captured and burned in a gas turbine for energy generation. Lower impacts were found in human health and ecosystems categories, as well as the total value, in the second scenario.

1. Introduction

The circular economy represents a way to address the current environmental and socioeconomic crises. It implies leaving behind the linear economy model (i.e. extract-produce-consume-throw away), and replace it with a new model that optimizes resource flows (including water, energy and waste) to minimize the generation of waste (Grdic et al., 2020). In this model, waste is used as a resource.

The unique characteristics of plastics allow them to play an important role on the path to a more sustainable and resource-efficient future. Global plastics production is expected to triple by 2050 from a 2015 baseline (World Economic Forum, 2016). Of particular interest is flexible packaging, since it is the fastest growing segment in the industry and is expected to grow from 1.34 trillion units to 1.8 trillion units in volume in 2023 (Euromonitor International, 2020). This growth is attributed to the numerous consumer and producer benefits that flexible packaging offers, including convenience, ability to withstand e-commerce distribution, and shelf-life extension of many products, e.g. foods. As the growth in flexible packaging production continues, the industry will need to readapt and take a more holistic approach to support this growing demand while considering end-of-life issues and the focus that has been placed on eliminating packaging waste.

A number of significant initiatives are already underway globally within the flexible packaging industry including, but not limited to: i) Circular Economy for Flexible Packaging (CEFLEX) – Designing for a Circular Economy Guidelines; ii) Ellen MacArthur Foundation – New Plastics Economy; iii) How2Recycle (SPC) and Association of Plastics Recyclers (APR) collaboration on flexible packaging guidance for recycling; iv) Materials Recovery for the Future (MRFF); v) UK Plastics Pact, including a specific roadmap for flexible packaging.

In Europe, the demand for flexible films in 2018 was estimated at 13–15 Mt, of which 8.5–9 Mt correspond to polyethylene (PE), 2–2.5 Mt to polypropylene (PP) and multilayer flexible plastics and the rest to other polymers such as polyethylene terephthalate (PET), polyvinyl

* Corresponding author.
E-mail addresses: marianml@ugr.es (M.A. Martín-Lara), josemoorg@gmail.com (J.A. Moreno), garciagarcia.ggg@gmail.com (G. Garcia-Garcia), sunil.arjandas@fcc.es (S. Arjandas), mcaleroh@ugr.es (M. Calero).

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chloride (PVC) and biodegradable films (PRE, 2020). In Europe, PE flexible films have a wide variety of applications, including 23% on food packaging, 22% on plastic bags/sacks, 18% on stretch film to bind or wrap items together, 9% on flexible packaging films supplied on rolls, and 7% on agricultural film (PRE, 2020). In 2018, the total input of PE flexible films to EU28 + 2 recyclers was between 2.2 and 2.3 MT, with the following split of sources: 14% household film, 44% of commercial and industrial film; 18% agricultural waste; 24% production scrap (PRE, 2020). Unfortunately, there are very few collection systems currently in place for household flexible films, as the development and growth of these materials came after the traditional municipal recovery facility installations were optimized for paper, metal, glass, and rigid plastics. Flexible films were not considered in the original designs of these facilities layouts, and so their sorting technologies are inefficient (Horodytska et al., 2018). Currently these materials are mostly sent to landfills, so their value is lost and an environmental impact is created. Globally and locally, there is much to be done to transform the value chain of post-consumer PE flexible films to a more circular and waste-free value chain.

Life-Cycle Assessment (LCA) is a methodology to analyze the environmental impact of a product, process or activity, taking it into account their complete life cycle, from the extraction of raw materials, to production, distribution, maintenance, reuse, recycling and disposal (ISO 14040, 2006; ISO 14044, 2006). Completing an LCA involves: i) compiling an inventory of energy and materials 'inputs' and emissions to the environment; ii) assessing the potential environmental impact associated with these inputs and emissions; iii) calculating the value of performance indicators to make decisions. The next section presents the most recent LCA studies that analyze the environmental impact of the treatment of plastics.

2. State of art of LCA to assess the treatment of plastics

In the last years, LCA has been extensively used to study the environmental impacts of plastics. Table 1 shows some of the most relevant recent studies that applied LCA to assess the treatment of plastic materials. It can be seen that a wide range of treatment options, as well as types of plastics, are considered in such LCA studies. However, limited information about the mechanical recycling of plastic flexible films is available. Only Horodytska et al. (2018, 2020) and Hou et al. (2018) studied the recycling of plastic films. Horodytska et al. (2018) provided a complete review about plastic films waste management technologies from post-industrial and post-consumer stages. They highlighted the lack of thorough LCAs on plastic films waste management systems. More recently, Horodytska et al. (2020) used LCA to assess the environmental impacts caused by an innovative upcycling process of printed plastic scrap. Finally, Hou et al. (2018) analyzed the environmental tradeoffs of various end-of-life strategies for plastic film waste. The authors claimed that more investigation is needed to collect data to better characterize the recycling, utilization, and end-of-life treatments of plastic films waste. Also, it is important to mention the recent work of López and Serna (2022) that review the LCA studies applied to bags and its end-of-life treatments. This review first provides a comparison of the methodologies used in each study to perform the LCA. Then, the review describes the results obtained in the different LCA studies discussing advantages and shortcomings of each assessment.

The aim of this study is to quantify the environmental performance of the mechanical recycling of post-consumer polyethylene flexible films. A case study of a real waste management system in Granada (Spain) is used. We assess such a system in detail to identify the processes that

Table 1
Recent studies that use LCA to assess the treatment of plastics.

Scope of the study	Reference
Conversion of flexible packaging plastic waste to pyrolysis oil and multi-walled carbon nanotubes	Ahamed et al. (2020)
HDPE and biodegradable plastic grocery bags	Ahamed et al. (2021)
Pyrolysis of plastic solid waste	Antelava et al. (2019)
Recycling postconsumer HDPE and PET	Bataineh (2020)
Recycling waste PP plastic	Bora et al. (2020)
Mechanical recycling, incineration and landfilling of waste plastics	Chen et al. (2019)
Single-use plastics: production, usage, disposal, and adverse impacts	Chen et al. (2021)
Moving from linear to circular household plastic packaging in Belgium: Prospective life cycle assessment of mechanical and thermochemical recycling	Civancik-Uslu et al. (2021)
Treatment of *Plasmix* (residues generated during plastic recycling operations)	Cossu et al. (2017)
Municipal solid waste management	Costa et al. (2019)
PP, PLA, PET, glass and cardboard + PE single-use and reusable cups	Cottafava et al. (2021)
Anaerobic digestion, materials recovery and secondary fuels production of municipal solid waste management	Cremiato et al. (2018)
Landfill, incineration, and gasification-pyrolysis of paper and plastic packaging waste	Demetrious and Crossin (2019)
Recycling of hard plastic waste collected at recycling centers	Faraca et al. (2019)
PET packaging	Gomes et al. (2019)
Mechanical recycling of waste plastics	Gu et al. (2017)
Resource multiple-life-cycle recycling waste PET bottles	Gu et al. (2020)
Plastic flexible films waste management	Horodytska et al. (2018)
Upcycling of printed plastic films	Horodytska et al. (2020)
Landfill, incineration and recycling of plastic film waste	Hou et al. (2018)
Post-industrial plastic waste recycling	Huysman et al. (2017)
Recycling plastic waste	Joachimiak-Lechman et al. (2020)
Environmental impacts of plastic packaging of food products	Kan and Miller (2022)
Application of life cycle assessment in municipal solid waste management: a worldwide critical review	Khandelwal et al. (2019)
Large-scale centralized and distributed small-scale facilities for sorting and recycling plastic bottles and takeaway containers	Kerdlap et al. (2020)
Plastic waste recovery into recycled materials, energy and fuels	Khoo (2019)
Substitution of PET bottles with glass bottles	Kouloumpis et al. (2020)
The dilemma of plastic bags and their substitutes: A review on LCA studies	López and Serna (2022)
Landfill, sorting and incineration of PET bottles	Martin et al. (2021)
Chemical recycling of PET, HDPE, LDPE, PP and PS	Meys et al. (2020)
Chemical recycling of post-consumer plastic waste	Rickert et al. (2020)
Recycling plastic waste	Rosmiati and Hadiyanto (2020)
Recycling plastic waste into pellets to be used in the production of asphalt mixes	Santos et al. (2021)
Recycling PET bottles	Schmidt et al. (2020)
The Cradle-to-Cradle Life Cycle Assessment of polyethylene terephthalate: Environmental perspective	Tamoor et al. (2022)
Life cycle assessment of bio-based and fossil-based plastic: a review	Walker and Rothman (2020)
Integrated municipal solid waste treatments (including plastic recycling)	Wang et al. (2020)
Production and recycling of PVC	Ye et al. (2017)
Plastic, stainless steel, glass, paper, bamboo and jute drinking straws	Zanghelini et al. (2020)

contribute the most to the overall environmental impact, and the impact categories more relevant, to be able to give recommendations to reduce such impact. In conclusion, this work evaluates, for the first time, the environmental impacts of mechanical recycling of post-consumer polyethylene films from the mixed fraction of municipal solid waste by the LCA methodology.

3. Materials and methods

This section describes how the LCA was carried out. The following four phases were followed, according to ISO 14040:2006 guidelines: goal and scope definition, inventory, impact assessment and interpretation.

3.1. Goal definition

The purpose of the present study is to quantify the life-cycle environmental impacts of the mechanical recycling of post-consumer PE flexible films and to quantify the contribution of each stage of the process to the total environment impact, with the purpose of identifying the most environmentally damaging process. The primary intended audience of the study is the waste treatment facility selected in the case study, which want to know the environmental impact of their recycling process of this material. It is also believed that this study would be useful for other waste treatment companies and for designers of plastic products. Potential audience of this study also includes other researchers working in this field, as well as policy makers involved in decisions regarding recycling of post-consumer waste. The results are not intended to be used in comparative assertions intended to be disclosed to the public.

3.2. Scope definition

3.2.1. Description of the analyzed recycling process

The post-consumer PE flexible film comes from the low-density polyethylene (LDPE) bales generated as rejection during the treatment of the rest fraction of municipal solid waste in the municipal recovery facility installations of the city of Granada (Spain). The recycling process is mechanical, so there are no unitary processes based on chemical or thermochemical routes (e.g. pyrolysis, gasification or incineration).

The LDPE bales, after being received and collected, are introduced into the process line by means of bale-holder equipment. This places them on a dosing belt, leading them to the bale opener. Here, the compacted mass is disintegrated. The material is then placed in a trommel for drying. The thermal fluid is made up of a stream of hot gases from the gas turbine attached to the installation. The injection of the gas jet also favors the disintegration of the material, as well as eliminates part of the dirt that accompanies it (humid organic matter).

At the exit of the trommel, the material is pre-crushed to a size of 20 × 20 cm. It is then passed through a cascade of three optical separators, which eliminates most of the impurities that initially accompanied the LDPE-film in the bullet. Impurities include paper and cardboard (hereinafter P/C), textiles and other plastics (PET, HDPE, PVC, PP and PS). These impurities are compacted and stored, to finally be dispatched for their management outside the limits of the installation. At the end of this process, the material has a PE purity of the order of 98% (excluding organic matter/dirt content).

In this state, the plastic that leaves the cascade of optics is led to a wet grinder, where the action of a pressurized water flow reduces the dirt content on the plastic while the blades reduce its size to 5 × 5 cm.

After crushing, the material is washed by means of decantation basins and centrifugal washers. The washing water is continuously purified in a small purification facility that the plant owns. Three chemical agents (coagulant, pH regulator and flocculants) are dosed to reduce the COD and BOD content of the washing water. In addition, a continuous flow of 2 m^3/h of fresh water is introduced into the washing line.

Having eliminated practically all the remaining dirt, the plastic is sent to thermal drying units (by air heated through electric resistances) and mechanical drying. After drying, the plastic is led to an extruder, where, by the action of electrical resistances, it begins to melt, first on the inner wall of the barrel (outer cylinder). As the melt grows, it detaches from the walls and falls into the spindle (internal worm), which in turn moves the material along the axis of the barrel. The extruder has a degassing system to avoid the formation of irregularities in the material. At the end of the route, the material is forced to pass through a nozzle (die), which gives the material the shape of a narrow cylinder. At its exit, the blades of the pelletization fractionate the filament, while putting it in contact with a continuous flow of water which solidifies the produced pellets.

Along with the water from the washing line, the water used in the wet disposer is also purified in the plant installation and later recirculated to the disposer. As a result of the treatment, a flow of sludge (humid organic matter) and a flow of residual water (2 m^3/h) is generated, which are drained and conducted to the wastewater treatment plant of the industrial estate (WWTP).

The LDPE streams which are generated throughout the process are separated from the normal process flow. The losses, generated mainly by material falling from the conveyor belts, are disposed of in a landfill next to the facility, along with all the wet organic matter (sludge and others) generated.

Fig. 1 shows the simplified block flow diagram of the analyzed industrial process.

The process is divided into four large areas of operation: Area 1: Sorting; Area 2: Washing; Area 3: Extrusion; and Area 4: Wastewater treatment. In Fig. 2 a simplified scheme of the operations included in each area is shown.

3.2.2. Functional unit

The production of 1 kg of recycled LDPE pellets (physical type functional unit) from post-consumer PE flexible films present in mixed municipal solid waste in Granada (Spain) was chosen as the functional unit.

3.2.3. System boundary

We followed a gate-to-gate approach to study the environmental impact associated to the production of the LDPE pellets. This means that the studied system includes the production process in the recycling plant where the pellets are obtained and excludes the use of the pellets in its final application. Fig. 3 shows the system boundary diagram of recycled LDPE pellets production.

The system boundaries exclude the stages of generation, collection and transportation of the mixed municipal solid waste (where the PE flexible films are found), following a zero-burden approach like in other LCAs of waste management (Garcia-Garcia and Rahimifard, 2019). Other stages excluded are preparation of the bales that takes place in the municipal recovery facility installations of the city of Granada (Spain), transportation between all the listed activities, manufacture of products from recycled pellets, and final disposal.

Specific considerations taken into account for the system boundary and inputs (reactants, energy, water, etc.) are listed below:

1. The production process is modelled in a steady state. For this reason, the impacts associated with the maintenance stages are not included in the study. Neither are considered the impacts of stopping the process and resuming it, which take place before and after maintenance.
2. The management of waste generated in offices, bathrooms and changing rooms is excluded.
3. The impact associated with the construction of the machinery used in the process is not included, as well as the impact of transportation from the factory to the plant gate.

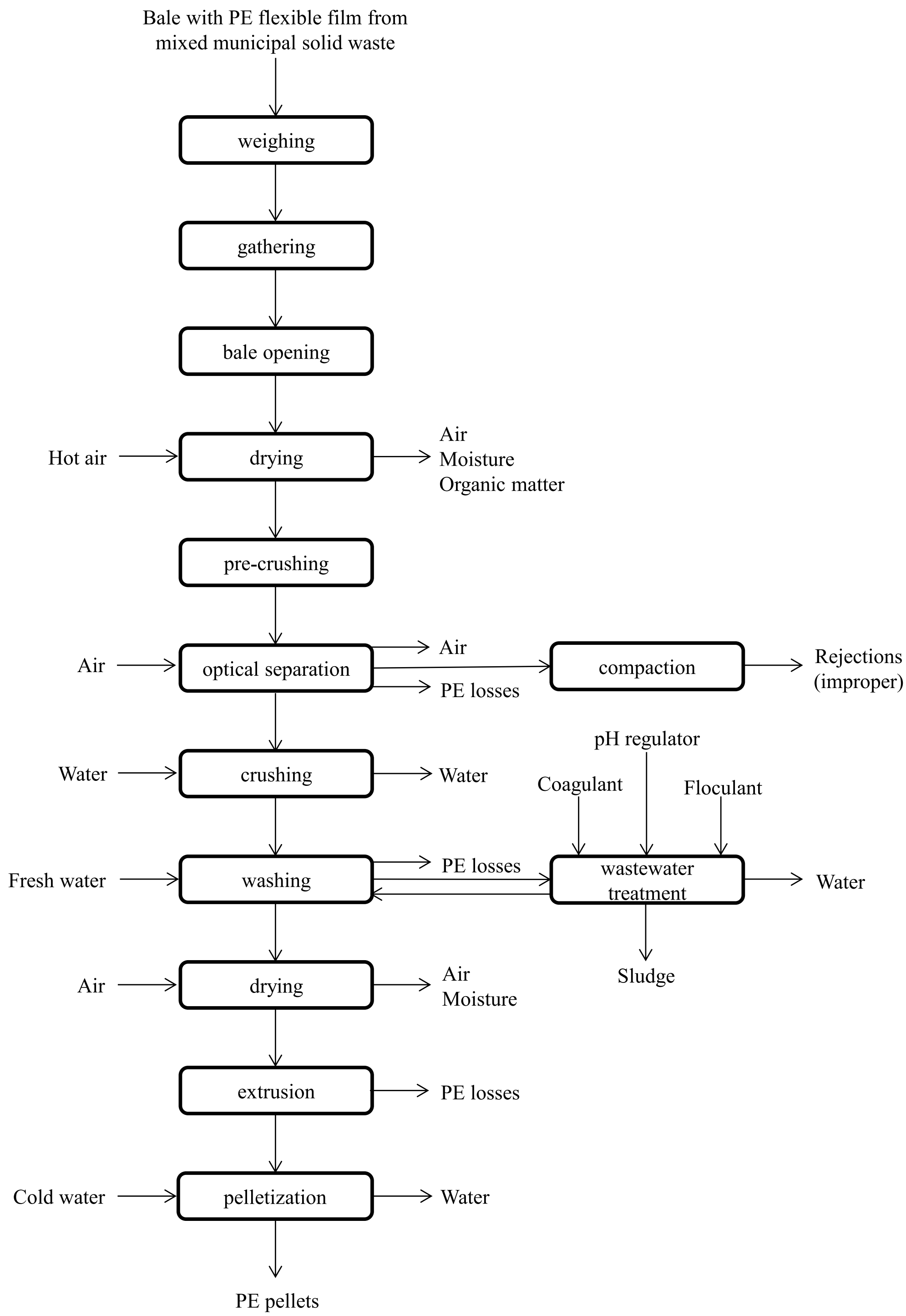

Fig. 1. Simplified block flow diagram representing the process analyzed.

4. The acoustic impact of the machinery during its operation, traffic, etc. are not considered.
5. Impacts due to the construction of the infrastructure that houses the production process (industrial warehouse with processing area, offices, changing rooms, etc.) are excluded.
6. The impacts attributed to the construction of the electrical network and transformer stations that supply energy to the plant are not considered.
7. Water flow rates for the process that are recirculated "indefinitely" are not included. Therefore, the impact of the zero-time filling of the washing line is not considered, and neither is the flow rates used in the wet grinders, as well as the cooling flow rate of the pelletizer.
8. Management of P/C and plastics (PET, HDPE, PVC, PP and PS) rejections obtained in the optical separators is excluded.
9. The construction of the bale carrier equipment used to feed the process line is excluded, as well as the impacts related to obtaining diesel fuel (manufacturing and transportation) burned by its engine.
10. With regard to the fresh water stream used to renew the process washing water: i) The impact of the construction of the water treatment plant (WTP) from which this flow is originated is not

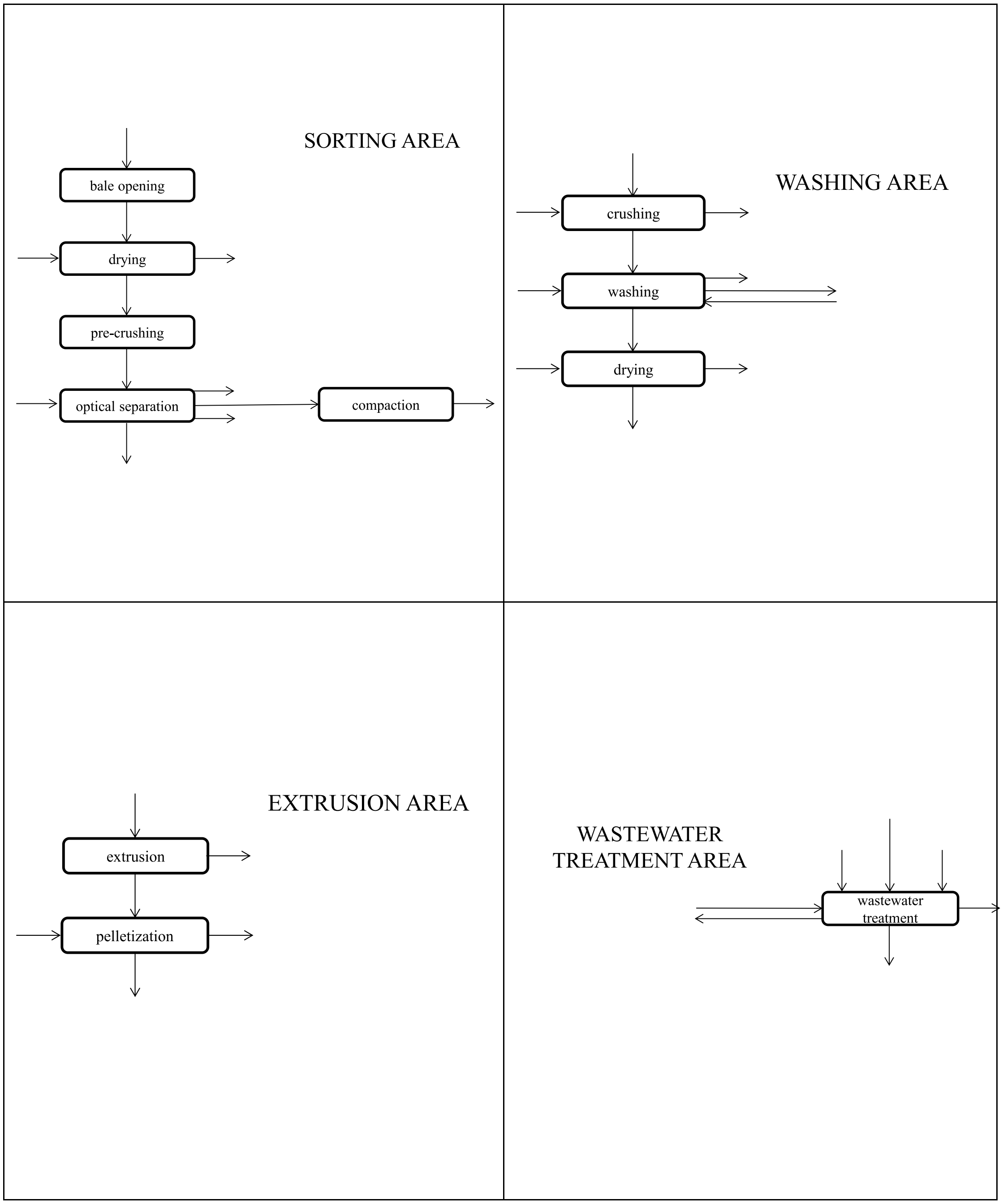

Fig. 2. Simplified scheme of units/operations/stages included in each area of the process.

considered; ii) The impact of the construction of the pipe network connecting the WTP and the recycling plant is not considered; iii) The impact of the construction of the electrical network that supplies said WTP is not included; iv) Regarding the reagents used for water treatment in the WTP: the impact of the construction of the chemical plants in which they are obtained is excluded and the impact of transporting them to the WTP is excluded; v) The treatment of waste resulting from the WTP is excluded.

11. Regarding the reagents used to treat the water from the recycling process (Zone 4 Water purification): i) The impact of the construction of the chemical plants in which they are obtained is excluded; ii) The impact of transporting them to the plant is excluded.
12. Regarding the WWTP to where the aqueous effluent that leaves Area 4 is directed: i) The impact of the construction of said WWTP is not considered; ii) The impact of the construction of the pipe network connecting the plant and the WWTP is not considered; iii) The impact of the construction of the electrical network that supplies the WWTP is not included; iv) Regarding the reagents used for the treatment of water in the WWTP: The impact of the construction of the chemical plants in which they are obtained is excluded; The impact of transporting them to the WWTP is excluded; v) The treatment of waste resulting from the WWTP is not considered.
13. The LDPE losses that are generated throughout the process, as well as the organic matter generated in the drying trommel and in Area 4 Wastewater treatment in the form of sludge, are sent to landfill. It was considered appropriate: i) To exclude the

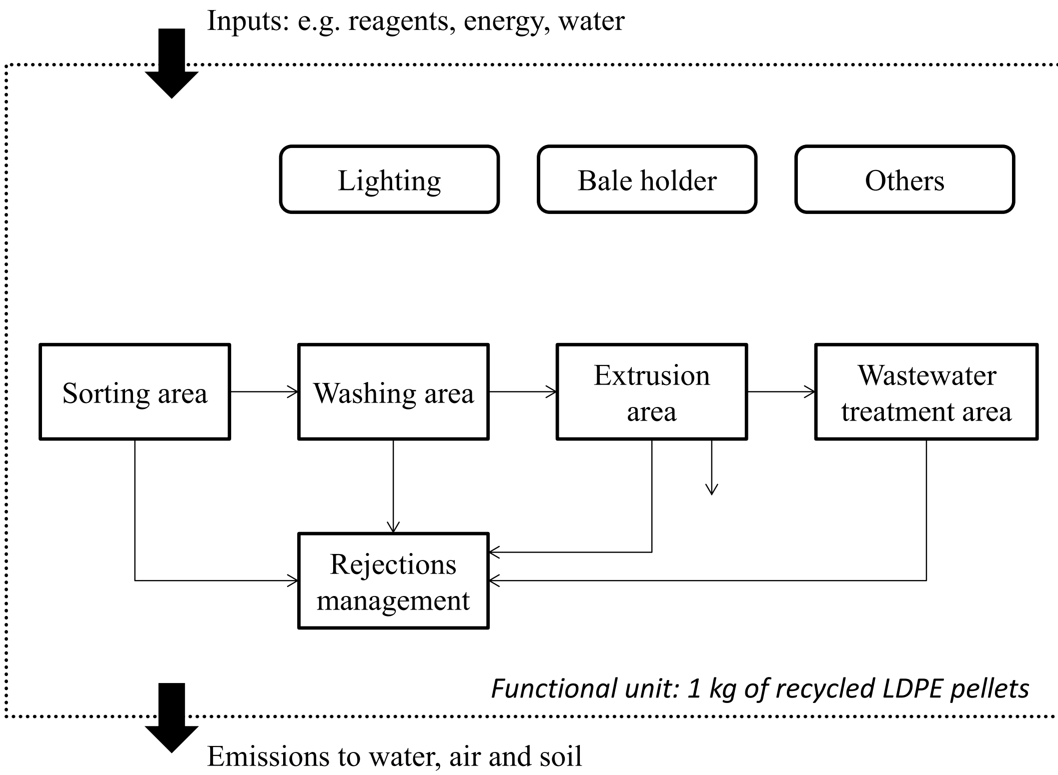

Fig. 3. System boundary diagram.

construction of the landfill; ii) To exclude the impacts of the construction of the mobile machinery of the landfill; iii) To exclude the impacts related to obtaining diesel fuel (manufacturing and transportation) used by mobile machinery; iv) To exclude the management of leachate.

3.2.4. Data sources

The primary data were taken from the Project "Post-consumption film plastic recycling from municipal solid waste (LIFE17/ENV/ES/000229)". Other data were obtained from the Ecoinvent 3.0 database available in SimaPro®, choosing processes defined mainly for Spain, Europe or Europe excluding Switzerland (ES, RER and Europe without Switzerland, according to the software nomenclature). When such options were not found in the database, global processes (GLO) were used.

3.3. Life cycle inventory (LCI)

All the material and energy inputs, waste outputs, and emissions to air, water and soil throughout the whole product life cycle are tabulated in Tables 2–4, referring to 1 kg of post-consumer recycled LDPE pellets.

For moisture quantification only the initial humidity of the bale was considered. The humidity acquired throughout the process was not taking into account due to not having enough information.

The emitted gases are the gases generated and released from the landfill disposal of waste generated during the mechanical recycling of plastic film. For the quantification, the same guidelines as in the 2019 National GHG Inventory (page 532) (MITECO. Ministry for Ecological Transition, 2019) were followed. This document used the IPCC reports

Table 2
Electricity inventory. Functional unit: 1 kg of recycled LDPE pellets.

Area	Operation	Electricity, kWh
Sorting	Bale opening	0.016500
	Drying	0.015000
	Pre-crushing	0.120900
	Optical separation	0.107940
	Compaction	0.032820
Washing	Crushing	0.062700
	Washing	0.17730
	Drying	0.18240
Extrusion	Extrusion	0.26430
	Pelletization	0.0066000
Wastewater treatment	Depuration	0.058986
Lighting		0.0136
Others		0.0144

Table 3
Material inputs and outputs inventory. Functional unit: 1 kg of recycled LDPE pellets.

Area	Inputs	Quantity
Washing	Water	2 L
Wastewater treatment	Poly aluminum chloride-coagulant	0.0081000 kg
	Deionized water for coagulant	0.036900 kg
	Caustic soda 50% (w/w)	0.024000 kg
	Polyacrylamide-flocculant	0.00027000 kg
	Deionized water for flocculant	0.089730 kg
	Aqueous effluent	2.1590 L
Bale holder[a]	CO_2 (100% oxidation)	0.0053113 kg
	N_2O	$9.3240 \cdot 10^{-8}$ kg
	NO_x	$2.4825 \cdot 10^{-5}$ kg
	NH_3	$6.3270 \cdot 10^{-8}$ kg
	Indeno(1,2,3-cd)pyrene – ID(1.2.3-cd) P	$2.6307 \cdot 10^{-11}$ kg
	Benzo(k)fluoranthene – B(k)F	$1.4486 \cdot 10^{-11}$ kg
	Benzo(b)fluoranthene – B(b)F	$2.7639 \cdot 10^{-11}$ kg
	Benzo(a)pyrene – B(a)P	$2.6307 \cdot 10^{-11}$ kg
	Lead – Pb	$8.6580 \cdot 10^{-11}$ kg

[a] Emissions calculated from the diesel fuel consumption data (0.001665 kg-referring to the functional unit). The emission factors proposed by the European Environmental European Environment Agency (2019a) and the IPCC (2006a) were used, the latter to quantify CO_2.

Table 4
Landfill disposal scenario as end-of-life treatment. Functional unit: 1 kg of recycled LDPE pellets.

Inputs/Outputs		Quantity
Dry organic matter, kg		0.27597
Moisture, kg		0.056111
PE losses, kg		0.21513
Emitted gas	Biogenic CH_4 –organic matter, kg/kg	0.21026
	NMVOC-organic matter, kg/kg	0.0012948
	TSP-organic matter, kg/kg	$1.8343 \cdot 10^{-6}$
	TSP-PE, kg/kg	$2.2100 \cdot 10^{-6}$

(IPCC, 2006b and 2006c) to quantify biogenic CH_4. The documents consulted for the estimate are:

- DOC content in % of dry waste (food waste): IPCC 2006a, 2006b, 2006c vol 5. Chapter 2. p. 15. Table, 2.4
- Methane correction factor (MCF-managed): IPCC 2006a, 2006b, 2006c vol 5. Chapter 3. p.16. Table, 3.1
- DOCf = 1 (it is assumed for the calculation that all biodegradable carbon degrades)
- Fraction of CH_4 in the generated landfill gas (F): IPCC 2006a, 2006b, 2006c vol 5. Chapter 3. p. 16
- Equations 3A1.16and 3A1.17: IPCC 2006a, 2006b, 2006c vol 5. Chapter 3. p. 40

The emissions of NMVOC (non-methane volatile organic compounds) and TSP (total suspended particles) were found according to the emission factors proposed by EMEP/EEA (Biological treatment of waste-solid waste disposal on land) (European Environment Agency, 2019b).

3.4. Life-cycle impact assessment (LCIA)

To evaluate the impacts of the production of 1 kg of post-consumer recycled LDPE pellets, the ReCiPe 2016 Midpoint (H) V1.03/World (2010) H method was used. This method develops LCIA results 18 single environmental problems (midpoint indicators). The Endpoint method was also used to aggregate results into three higher aggregation levels: environmental impact to human health, damage to ecosystems, and damage to resource availability. As the environmental impact scores of LCAs are often presented in units that are difficult to compare, normalization was also performed by using the ratio of the impact per unit of emission divided by the per capita world impact value of the year 2010. Results were also aggregated into three areas of protection: human health, ecosystems and resources.

All unit process data process models and life-cycle inventories were constructed and compiled using the LCA software SimaPro® 9.0.0.49 PhD, which was also used to calculate the results for the LCIA.

3.5. Interpretation

Interpretation of the results of the LCA study serves two purposes (EUR-Lex, 2013):

- To ensure that the LCA model addresses the goals of the study and fulfill its quality requirements.
- To develop recommendations and conclusions from this analysis, for example to make environmental improvements.

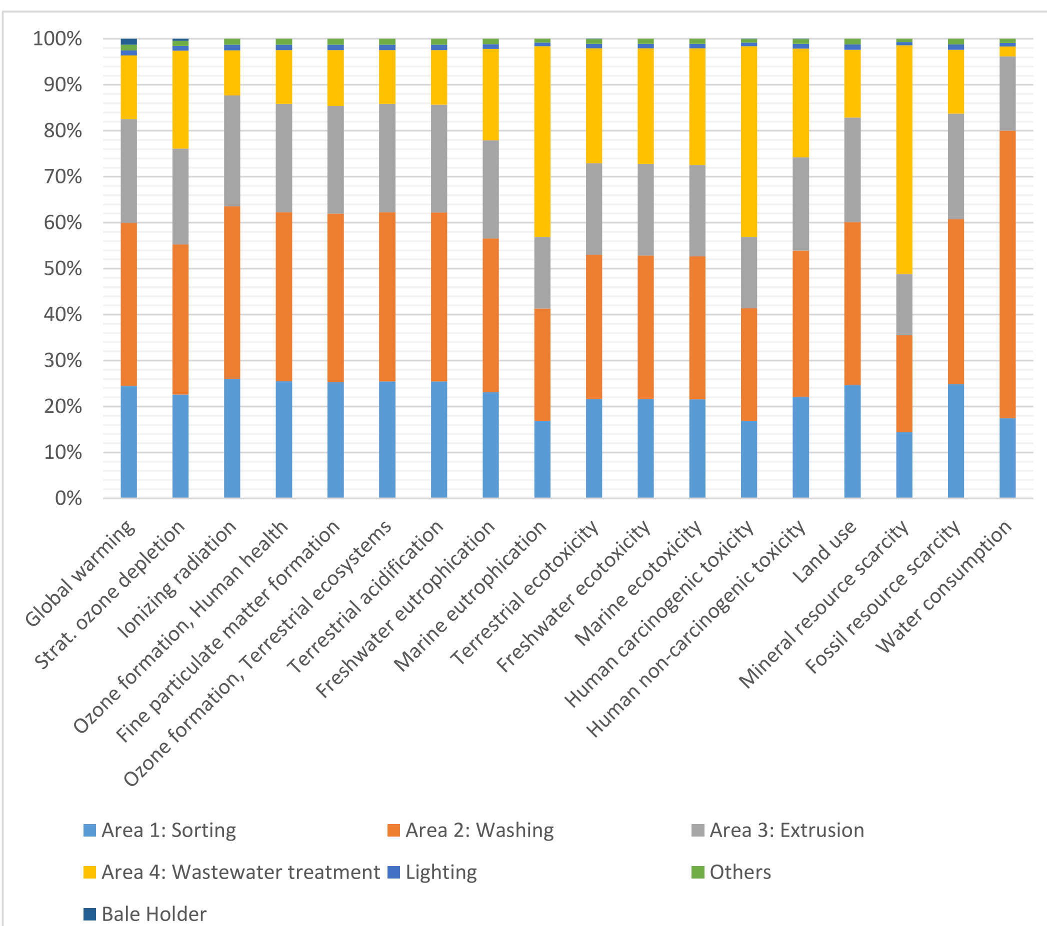

Fig. 4. LCIA results of the characterization of the process by the ReCiPe 2016 Midpoint (H) V1.03/World (2010) H methodology.

To meet these objectives, the result interpretation phase includes four key steps an assessment of the robustness of the LCA model and a description of the conclusions, limitations and recommendations from the study.

4. Results and discussion

4.1. Environmental impact results

Fig. 4 shows the LCIA results for the analyzed process using the ReCiPe 2016 Midpoint (H) methodology. The numerical values can be found in Table S1 in Supplementary Material. For all environmental impact categories, the contribution of lighting, others and bale holder is minimal. The areas with the highest installed electrical power are generally those with the greatest impact. These areas correspond to washing and sorting. There are two areas which contributes significantly to two environmental impact categories: wastewater treatment for mineral resource depletion (50%) and washing for water consumption (63%).

For a better interpretation of the data included in Table 4, the ReCiPe 2016 Endpoint (H) methodology was used to normalize and group impact categories into three areas of protection: Human Health (damage to human health), Ecosystems (damage to ecosystems) and Resources (resource consumption). The results of this normalization step, in millipoints (mPt) as per ReCiPe 2016 Endpoint method, are shown in Fig. 5. This figure is useful to compare relative differences between areas and between environmental impact categories. The numerical values can be found in Tables S2–S3 in Supplementary Material.

Fig. 5 shows that the area that causes the greatest environmental impact is Area 2: Washing, which represents 35.6% of the total impact, followed by Area 1: Sorting, with 24.3% of the total impact. Extrusion and wastewater treatment areas contribute with 22.5% and 14.8%, respectively. The rest of areas only represent 2.8%.

The most relevant environmental impact for all areas is to human health, with 21.38 mPt, of which 7.61 mPt are attributed to Area 2: Washing. Regarding the unit processes (included in process areas), the one with the highest impact is Extrusion (from Area 3: Extrusion) which has a score of 4.69 mPt, followed by the unitary process of Washing (from Area 2: Washing) with a score of 3.26 mPt. The impact to resource consumption contributes the least to the overall environmental impact, mostly due to the exclusion of the construction stages of the building, machinery and the chemical plants from which the reagents directly involved in the recycling process are obtained.

Furthermore, two end-of-life scenarios for the generated waste have been included in Fig. 5. The objective was to assess the impacts of the end-of-life stage for the waste generated during the mechanical recycling process and its influence in the final results when considering different waste management scenarios. The first end-of-life scenario considers the landfill disposal of the humid organic matter generated in the washing process and the landfill disposal of the PE losses during the mechanical recycling. In this scenario it was considered that all the CH_4 resulting from the anaerobic degradation of the organic matter was not recovered and it was directly released into the atmosphere. In this case, human health impact was very high (37.20 mPt). In the second end-of-life scenario, all the CH_4 generated is captured and burned in a gas turbine for energy generation. Much lower impacts were found to human health (0.052 mPt) and ecosystems categories (0.0047 mPt), as well as the overall environmental impact (0.0057 mPt), in this second scenario compared to the first scenario (40.93 mPt). In conclusion, for the first scenario, end-of-life impacts would dominate over all other areas. The differences in the results of the two scenarios reinforce the importance of clearly reporting the scenario considered in the waste treatment.

The real situation foreseen for the landfill in Granada is assumed to be between both scenarios, closer to the second scenario where CH_4 is captured to be burned in a turbine. It was decided to present the results based on the two extremes (i.e. scenario 1 and 2) because the real situation is difficult to be defined: not all the CH_4 generated is captured, part of it is oxidized in the areas near the surface of the landfill, and a small percentage of the CH_4 captured to be burned is released unburned in the exhaust gases.

4.2. Identification of the main contributing units/operations/stages to the LCA results

To facilitate the interpretation of the LCA results and to formulate adequate conclusions, it was decided to include the contribution of each of the stages of each area with the greatest impact as a single score (expressed in %). Fig. 6 shows the single scoring network using ReCiPe methodology 2016 Endpoint (H) V1.03/World (2010) H/A.

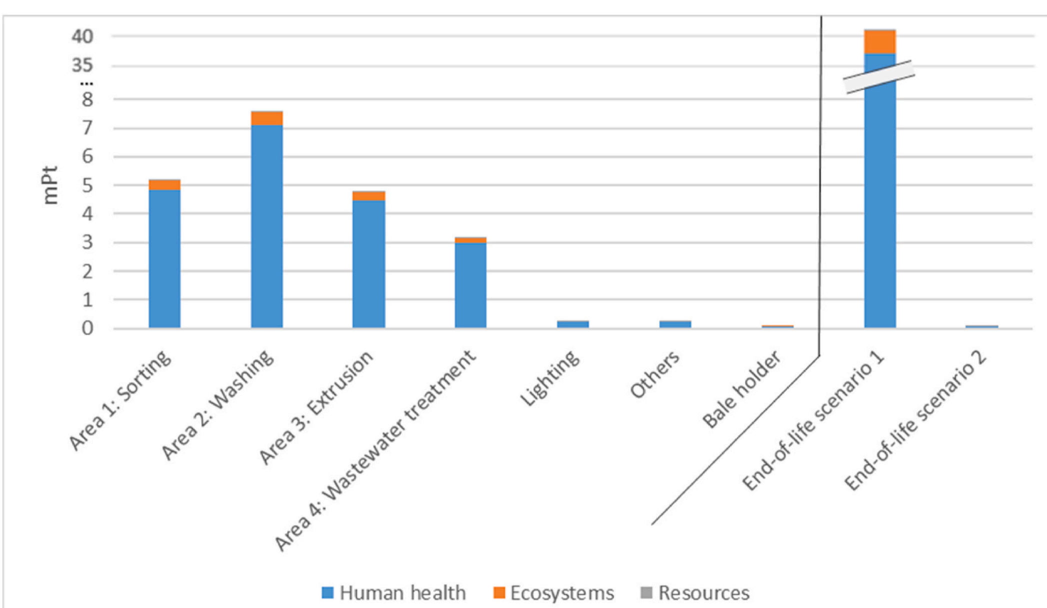

Fig. 5. Normalized aggregated results of the process by the ReCiPe 2016 Endpoint (H) V1.03/World (2010) H/A.

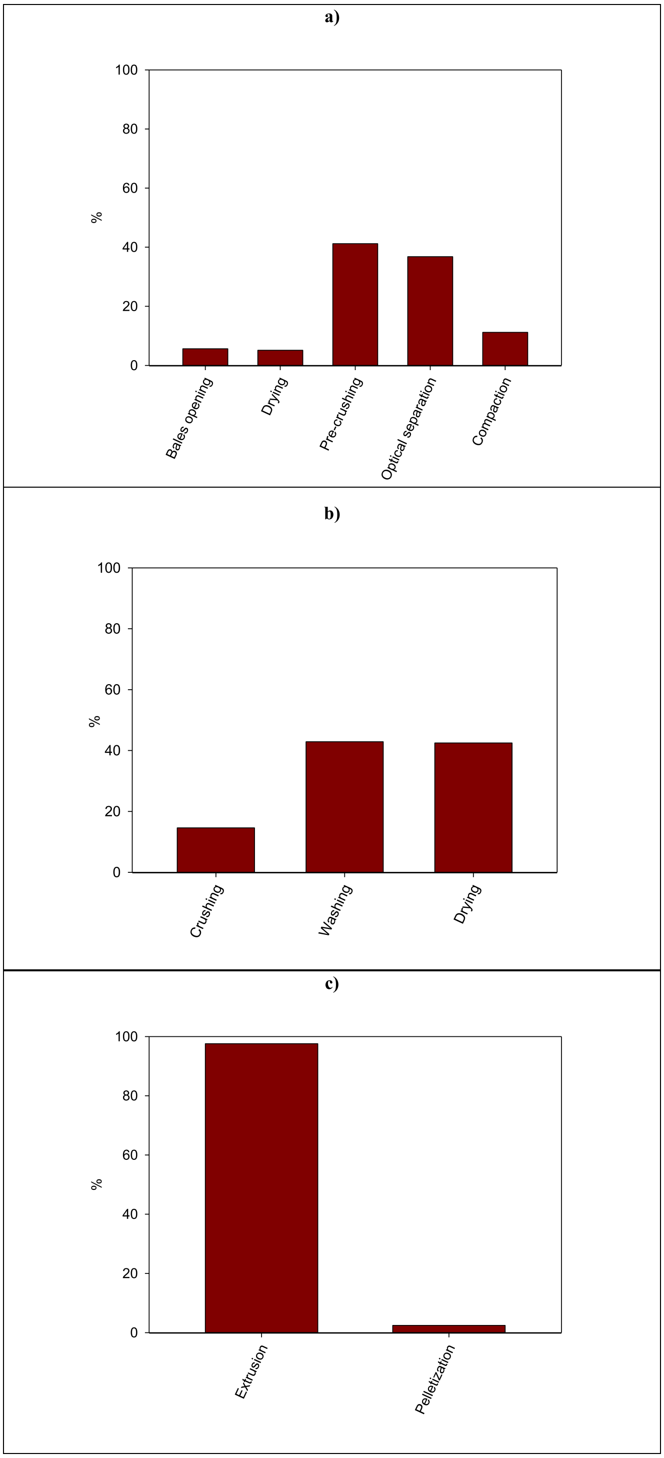

Fig. 6. Percentage contribution to the single score of the main units/operations/stages of the different process areas using the ReCiPe 2016 Endpoint (H) V1.03/World (2010) H/A methodology. a) Sorting area; b) Washing area; c) Extrusion area.

Fig. 6 shows that the critical unit processes in each area are:

- Area 1: Sorting.
  - Pre-crushing: 41.2% of the total impact of this area.
  - Optical separation: 36.8% of the total impact of this area.

The impact of this area is due to exclusively the electricity consumption of the machinery.

- Area 2: Washing.
  - Washing: 42.9% of the total impact of this area.
  - Drying: 42.5% of the total impact of this area.

The impact of this area is attributed to the electricity consumption of the unit processes (98.5%) and the consumption of fresh water from the network for the renewal of the line water (1.5%).

- Area 3: Extrusion.
  - Extrusion: 97.6% of the total impact of this area.

The impact of this area is due to the electricity consumption of the extrusion and pelletizing machinery.

- Area 4: Water purification.
  - Consumption of sodium hydroxide as a pH regulating agent: 34.8% of the total in this area.
  - Consumption of poly aluminum chloride as a coagulating agent: 33.5% of the total in this area.

As there is only one processing unit in the water purification area, this area was not included in Fig. 4.

4.3. Assessment of the robustness of the LCA model

In order to ensure that the results and conclusions presented in this work do not depend on the calculation methodology used, a comparison has been made with the results obtained using different methodologies, which are also widely used: EPD (2018) V1.00 and CML-IA baseline V3.05/EU25. The results obtained by using these two methods can be found in Table S4 of Supplementary Materials document. Despite the fact that the comparison of the results between different methodologies is not always possible, as they use different characterization and normalization factors, the impact of the common categories for each area is similar in the three methodologies considered. It can be concluded that the critical areas of the process remain the same regardless of the selected methodology. It must also be considered that the selection of the version of the method (i.e. Hierarchist (H), Egalitarian (E) or Individualist (I)) obviously influences the results, based on the degree of optimism for future projections. In the results reported, the Hierarchist version was used, which is the default ReCiPe method and most widely accepted.

Simplifications and excluded information have an obvious impact on the numerical results obtained. One example is the exclusion of the transport of reagents used in Area 4: Wastewater purification, from the factory to the gate of the PE recycling plant. To evaluate the magnitude of this exclusion for this Area 4, the transport of the coagulant, pH regulator and flocculant was evaluated. The transport data used for this estimation were those defined in the ecoinvent database, since at the date of writing this article, the real path that the reagents follow up to the plant is unknown. This defined dataset includes maritime transport, although the actual future route followed by the reagents is probably only by land. This makes following estimation conservative in nature. The results of the single score indicator (in mPts) can be seen in Table 5. In the table, A reflects results of wastewater treatment as it was previously defined, B the results of wastewater treatment including predefined transport for reagents, C the results of the assembly of the process and D, the results of the assembly of the process having considered alternative B above. Results show that considering the transport of the

Table 5
Estimated effect of reagent transport on the final single score of the Assembly of the process.

	A	B	C	D
Unique final punctuation, mPt	3.1748	3.6989	21.381	21.905

three aforementioned reagents would mean an increase of only 2.45% in the final single score of the assembly of the process. As mentioned above, these values are conservative since transport routes with lower impacts are foreseen, and therefore the difference between results (A-B and C-D) is expected to be smaller.

It is difficult to make comparisons with LCAs carried out by other researchers since many factors influence the final results. These factors are related to the goal of the LCA, the selected process, data used, assumptions, the functional unit, the boundary limits of the system and the LCIA method. In spite of this, our LCA results were compared with those obtained by PlasticsEurope in a similar study (PlasticEurope, 2014).

The LCA carried out by this organization for 1 kg of LDPE virgin included, in addition to the production stage, the extraction of raw materials and their transport to the plant. Therefore, the values obtained by PlasticsEurope are expected to be notably higher than those of our LCA, since they include more stages. The inclusion/exclusion of life cycle stages and related assumptions makes it impossible to directly compare specific stages from the recycling process on a one one-to-one basis. Table 6 shows the comparison of the overall results for the common environmental impact categories for both studies.

The results for our study were recalculated with the CML-IA baseline V3.05/EU25 evaluation methodology to be able to make a fair comparison between both studies. The values presented in Table 6 show that the results obtained are consistently lower than those reported by PlasticEurope (2014), as expected, except for the category abiotic resource depletion. This may be due to differences in the limits considered for the study, as well as the fact that the comparison is made between recycled and virgin LDPE.

Additionally, the results obtained by others authors are commented here, taking into account that the system boundaries of each study differ. Gu et al. (2017) investigated the LCA of mechanical recycling of plastic of a plastic recycling company in China using the mid- and end-point ReCiPe methods. Their results show that the extrusion process is the process contributing the most to the overall impacts, except for ozone depletion potential. Pelletization and washing processes contribute significantly too. In our results, the extrusion process has associated a lower environmental impact than washing processes, but much higher than the pelletization process. The shredding and transport processes contribute the least to the results of each environmental impact category and the total impacts in their study.

Faraca et al. (2019) undertook an environmental and financial assessment of hard plastic waste collected at Danish recycling centers. The functional unit (FU) chosen was the management of 1 t of post-consumer hard plastic (53% PP, 19% PE, 2% PET, 1% PS, 10% other polymers and 15% impurities). The authors considered two mechanical recycling options (a simple and an advanced configuration) and a conversion through pyrolysis. Their results show that the simpler mechanical recycling provided the largest environmental savings in the largest number of impact categories. In terms of global warning potential, the authors indicate that only the simpler mechanical recycling option provided environmental savings (−717 kg CO_2eq/FU), whereas the rest of scenarios resulted in a net burden to the environment (374 kg CO_2eq/FU for pyrolysis conversion and 940 kg CO_2eq/FU for advanced configuration mechanical recycling). In our study, lower environmental impacts were obtained when the CH_4 generated would be captured and burned in a gas turbine for energy generation.

Table 6
Comparison between the values obtained in this study and those by PlasticsEurope.

Environmental impact category	This study	PlasticEurope (2014)
Global warming, kg CO_2 eq	0.416	1.87
Acidification, kg SO_2 eq	0.00319	0.00436
Ozone layer depletion, kg CFC-11 eq	$7.26 \cdot 10^{-8}$	$8.20 \cdot 10^{-7}$
Depletion of abiotic resources (fossil fuels), MJ	4.72	72.8
Abiotic resource depletion, kg Sb eq	$3.18 \cdot 10^{-7}$	$5.2 \cdot 10^{-8}$
Eutrophication, kg PO_4^{3-} eq	0.000813	0.00125

Chen et al. (2019) applied LCA to evaluate the environmental impacts of mechanical recycling of 1 t of plastic waste (PE, PP, PVC, ABS, PS and PET) in China. Their results showed that the extrusion and transportation contribute significantly to all environmental impact categories, except for particulate matter formation potential. In contrast, our results show a smaller contribution of the extrusion process to the results for each environmental category, compared to the sorting and washing processes. Our system excluded transportation, as explained in Section 3.2.3. In the aforementioned study by Gu et al. (2017), transportation contribute the last to the overall environmental impact.

Garraín et al. (2008) calculated the CO_2 emissions for the recycling of 1 kg of HDPE, obtaining a value of 0.353 kg CO_2. Hsien (2019) evaluated the recycling process of 1 kg of plastic mixture determining an emission of around 0.400 kg CO_2 eq. Both values are similar to those obtained in our work (0.416 kg CO_2 eq.).

Hou et al. (2018) applied LCA to assess the environmental impacts of various plastic film waste treatment systems: landfill disposal, incineration, recycling and recycling of recyclable waste. The authors proved that there is an environmental advantage for recycling plastic film waste rather than landfill disposal or incineration. Recycling appears to be particularly favorable when the plastic film waste is recovered from mixed waste rather than from recyclable waste. The main environmental benefit is that recycled plastic films substitute virgin materials and avoid the environmental impacts associated with processing of these materials.

It is important to note that, as indicated above, it is difficult to compare LCA studies, because the different methodologies, functional units, boundaries, data used for the Life Cycle Inventory, environmental impacts evaluated, and LCIA method used. In addition, our LCI data consider real local conditions that reflect the current situation of the geographical location where the study was carried out. However, this also means that the specific data and assumptions used for the results may differ in other latitudes. In spite of this, the results obtained by other researchers described in this section are consistent with our results obtained.

5. Conclusions and recommendations

We applied the LCA methodology to quantify the environmental impacts associated to the production of 1 kg of recycled LDPE pellets. Our results show that the environmental impact caused by the process is dominated by the impact to human health caused by the washing area. The overall environmental impact triples when considering that the humid organic matter generated in the washing process and the PE losses during the mechanical recycling are sent to landfill. An end-of-life scenario in which the methane generated is captured and burned in a gas turbine for energy generation has a negligible environmental impact.

Based on the results obtained, the following recommendations are proposed:

- Since the environmental impacts are strongly linked to the installed electrical power, electricity supply from renewable energy sources should be encouraged.
- The machinery corresponding to the unit processes with the greatest impact, Extrusion and Washing, should be kept in good condition at all times. In this way, the mechanical performance (amount of electrical energy that is translated into effective mechanical work) is at its maximum level. It is important to focus on the general condition of the machinery in the most critical areas, as a reduction in their impact or an optimization of their performance would generate the greatest overall environmental benefit.

- If new machinery is purchased, energy efficiency criteria should be considered, as this significantly affects the environmental performance of the entire process.
- Since the main impacts associated with Area 4: Wastewater treatment are those related to the consumption of chemical agents for the regulation of pH and coagulation of organic matter, their dosage should be optimal. This implies that the chemical agent/water ratio to be treated is adequate and it is not being dosed in excess. Also, the automatic dosing systems (valves) should be kept in good condition. The state of the piping framework associated with the dosing system (e.g. elbows, diversifications) should be periodically checked.
- A precise comparative LCA that allows determining whether the current alternative of landfill disposal of rejects (sludge and waste) could be replaced by composting to obtain biostabilized material should be performed. This disposal scenario is of interest because in the MSW treatment plant next to the mechanical recycling warehouse there is already infrastructure available for composting according to the overturned pile technique.
- Workers should be trained to efficiently use the bullet-holder equipment in order to avoid excessive consumption of diesel fuel.
- Chemical reagents should be supplied from locations nearby the recycling plant when possible.
- The developed model should be maintained and updated to consider future scenarios with new machinery and/or other reagents, in order to determine the optimal scenario from an environmental point of view.

In conclusion, although the mechanical recycling of plastic waste may be considered a sustainable waste management practice, we have demonstrated that this treatment also creates an environmental impact that must be taken into account in future plans to manage post-consumer plastic waste.

CRediT authorship contribution statement

M.A. Martín-Lara: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Validation. **J.A. Moreno:** Data curation, Methodology, Software, Investigation. **G. Garcia-Garcia:** Software, Writing – review & editing. **S. Arjandas:** Resources, Funding acquisition. **M. Calero:** Conceptualization, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132625.

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