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ORIGINAL PAPER

Evaluation of the environmental impact of a plastic sprayer through life cycle assessment: an industrial case study

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Abstract
The use of plastics for the production of household objects represents a considerable fraction of the global plastic market. In this study, an environmental impact assessment was performed to identify the environmental burdens associated with the production of plastic trigger sprayers. The environmental impact of the analysed trigger sprayer is mainly determined by the extraction of raw materials, electricity consumption in the production stage and end-of-life treatment of wastes. The application of three improvements to the traditional process leads to a significant decrease in the environmental impact across all the considered impact categories: the benefits mainly arise from the use of renewable electricity and partly from the substitution of virgin material with recycled one. The carbon footprint related to a single plastic sprayer is decreased of around 23% upon the modifications applied to the traditional process, i.e., from 0.099 kg CO_2 eq down to 0.077 kg CO_2 eq that reported to the annual production of 15 million pieces, would lead to a reduction of around 339 ton CO_2 eq released to the atmosphere. The obtained results indicate that to further improve the environmental performance of plastic dispensers (and of plastic objects in general), technologies suitable for the processing and manufacturing of recycled materials should be implemented. This will be achieved only through the improvement of a collection, sorting and recycling system able to provide high-quality secondary materials. Finally, the industrial process should be optimized decreasing the production scrap, using renewable energy sources and promoting its reuse for multiple times.

Keywords Dispenser · Carbon footprint · Recycled plastic · Renewable energy

Introduction

In the last decades, the continuous increase in global demand for materials has caused the generation of hazards for human health and environment (Monteiro et al. 2017; Kamau-Devers and Miller 2020). One of the most rapidly growing markets is that of plastics, with a 28% increase in the global demand between 2007 and 2018 (Plastics Europe 2017; Plastics Europe 2019). Among the different types of plastics, in 2020, polyethylene (PE) and polypropylene (PP) covered the 37% to the plastic demand in Europe (Plastics Europe 2019; Plastics Europe 2021). One of the advantages of plastic that determines its enormous use, is the low cost that derives from the inexpensive fossil fuels feedstock used in the production process (Billington et al. 2014). On the other hand, the main disadvantage is related to the limited resistance to environmental deterioration that makes plastic wastes hazardous for human health and biodiversity (Ryan et al. 2009; Jambeck et al. 2015). In the United States, the plastic content in the municipal plastic wastes increased from 1% in 1960 up to 10% in 2000 (U.S. Environmental Protection Agency (EPA) 2010). The dispersion of plastic debris is causing great concern because their fragmentation in small particles caused by weathering renders the tracing and the removal from marine environment extremely difficult, with possible ingestion even by small marine invertebrates (Barnes et al. 2009; Thompson et al. 2009; Goldstein and Goodwin 2013; Obbard et al. 2014). The most critical aspect related to plastic wastes is related to single-use objects (Kamau-Devers and Miller 2020). With the Waste Directive 2006/12/EC, the European Commission

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introduced the so called "hierarchy of wastes" that identified a preference order for end-of-life option of wastes: (i) prevention or reuse, (ii) recycling and recovery, (iii) disposal (European Parliament 2006). With the Waste Framework Directive 2008/98/EC, the hierarchy of wastes has been updated as follows: (i) prevention, (ii) reuse, (iii) recycling, (iv) recovery, (v) disposal (European Parliament 2008). A different hierarchy can be applied only in case of more environmentally favourable options (Manfredi et al. 2011; Lazarevic et al. 2012). Due to these European regulations, from 2006 to 2020 the amount of plastic sent to recycling has doubled. However, in 2020 the amount of plastic waste sent to landfill was still as high as 23% (Plastics Europe 2006; Plastics Europe 2019).

In recent years, due to the concerns related to plastic pollution in the environment, the research on possible use of post-consumer-resin (PCR) as an alternative to virgin ones has been carried out (Cavalieri and Padella 2002; Hahladakis and Iacovidou 2019; Franz and Welle 2022). In particular, it has been found that the decontamination of plastic wastes requires extensive processing and cleaning operations, resulting in a very difficult use of plastic scraps with maximum proportions in the virgin materials of around 5 wt%. (Awaja and Pavel 2005; Chilton et al. 2010). These problems have enforced, for example, the bottle-to-bottle recycling process of polyethylene terephthalate (PET) that, also thanks to sophisticated decontamination processes, allows the production of PET bottles containing up to 50 wt% of post-consumer PET (Welle 2011). For the other polymers, the maximum amount of virgin material that can be replaced with recycled one is much lower: around 27% in case of polyethylene and 23% in case of polypropylene. The average recycling rates are around 26% for PET, 8% for polyethylene and 3% for polypropylene (Plastic recyclers Europe 2020, 2022).

The advances on plastic recycling and on the research of new polymers need the related consequences to be properly understood in terms of potential environmental impact, carefully considering the application field. The use of recycled materials or bio-based polymers is not, indeed, automatically the best choice due to several aspects that need to be considered, such as the electricity type used in the production process (Koskela et al. 2014; Biganzoli et al. 2018), the end-of-life treatment applied to wastes (Rossi et al. 2015), the type or the amount of packaging (Ross and Evans 2003; Raugei et al. 2009), the transport operations related to the process (Andersson and Ohlsson 1999; Sim et al. 2006). These considerations show the importance of using an approach able to evaluate the environmental impact considering the entire life cycle of a product. A valuable tool that allows such kind of evaluation is called Life Cycle Assessment (LCA). LCA allows to evaluate the potential contribution that a product has in the environment, considering the whole life cycle, from extraction of raw materials, to production, use, transports, reuse/recycling and final disposal (Baumann and Tillman 2004).

Considering the lack of studies on the environmental impact of plastic objects for household use and the fact that this sector (along with leisure and sport equipment) represents 4.3% of the total European plastic market (Plastics Europe 2018), this work aims at studying the environmental impact of a trigger sprayer, with a focus on the possible beneficial effects deriving from some modifications applied to the traditional production process (i.e., use of renewable energy in the production process, partial replacement of virgin material with recycled one, reduction in the number of polymer species required for a plastic product). Primary data were collected from an Italian company leader in the production of plastic sprayer for healthcare, home, personal care, fragrance and garden.

Materials and methods

According to ISO 14040 (International Standard Organisation 2006a, b) and 14044 (International Standard Organisation 2006a, b) standards, this LCA analysis has been divided into four different phases: goal and scope definition ("Goal and scope definition" section), inventory analysis ("Life cycle inventory" section), life cycle impact assessment ("Results and discussion" section) and interpretation of the results ("Conclusion" section). The SimaPro™ software version 8.4, supplied by Pré Sustainability (Amersfoort, Netherlands) was used for the processing of data.

Goal and scope definition

LCA has been applied to this study to:

- evaluate the environmental performance of trigger sprayers for house-cleaning products;
- quantify the possible benefits arising from three variants applied to the system (use of renewable electricity, substitution of polyoxymethylene with polypropylene, partial substitution of virgin polypropylene with recycled one) with the aim of decreasing its environmental impact.

System description

A trigger sprayer is an object designed to release a specific amount of liquid that can be soap, detergent, water, etc. In this study, according to the PCR 2013:09 (International EPD system 2019), only the sprayer is considered, the manufacturing of the container and the filling process is not taken into account because typically they are not under the control of the sprayer manufacturer. The object considered in this study is a trigger sprayer designed for the distribution of liquid detergents. The components of the trigger sprayer are listed in Table 1.

The different components of the sprayer are produced by transformation processes common to plastic products that cannot be specified due to confidential reasons. The second step is the assembly of the different components of the sprayer, followed by the packaging with a cardboard container. Finally, they are palletized with a polyethylene film and delivered. The sprayer object of the study is specifically designed for household use and not for professional use: this means that is not intended to be reused. With the aim of decreasing the overall impact of the system, the adoption of three variants was considered: the use of certified electricity from renewable resources, the substitution of POM with PP for the production of the spring (component 10) and the replacement of virgin PP with post-consumer PP (commercial grade) for the substitution of components 2, 3, 9.

Functional unit

The functional unit of the process is one trigger sprayer, as specified in the PCR 2013–09 (International EPD system 2019). The trigger sprayer object of this study is designed to reach at least 5000 actuations, equivalent to a distributed volume of around 5 l. The producer is an Italian company leader in the production of plastic sprayers for healthcare, home, personal care, fragrance and garden (the name of the company is not reported for confidential reasons). Around 15 million pieces of this trigger sprayer were produced during the reference year (2019) considered for the study.

Table 1 List of the components of the trigger sprayer

Component	Function	Material
1	Body	PP
2	Cap	PP
3	Shroud	PP
4	Gasket	PE
5	Tube	PP
6	Valve	Technical polymer*
7	Piston	LDPE
8	Nozzle	LDPE
9	Trigger	PP
10	Spring	POM
11	Foamer	PP

PP polypropylene, *PE* high-density polyethylene, *LDPE* low-density polyethylene, *POM* polyoxymethylene

*The polymer used for this component cannot be disclosed for confidential reasons

System boundaries

The analysis was carried out using a "cradle to grave" approach. Therefore, the system boundaries include:

- Upstream processes:
  - Raw materials production (i.e. PP, PE, POM)
  - Primary and secondary packaging production (i.e. cardboard, packaging film, pallet)
  - Auxiliary materials production (i.e. lubricants, electric/electronic components)
- Core processes:
  - Manufacturing, assembly and packaging of the sprayer
  - End of life of manufacturing waste and of primary packaging (recycling, incineration, landfilling)
  - Transport of raw materials, components and secondary packaging to the production plant
- Downstream processes:
  - Distribution of the sprayer
  - End of life of the sprayer and of the secondary packaging material (recycling, incineration, landfilling)

Cut-off

As reported in the PCR, data for elementary flows to and from the product system contributing to a minimum of 99% of the declared environmental impacts have been included.

Data quality

Primary data regarding core processes and the distribution of the sprayer were directly provided by the producer and regarded a production plant located in north-east Italy. Data are referred to the year 2019. Background data (such as raw material extraction, vehicles, the Italian electricity mix, waste treatments), taken from the Ecoinvent v. 3.5 database (cut-off by classification approach), were used. In few cases (i.e. polyoxymethylene production), the Industry Data 2.0 Database was used.

Selected impact indicators

The environmental impact assessment has been evaluated using the EPD 2018 method (v1.04) and included 8 impact

Table 2 Inventory of the materials used for the production of the sprayer, of the secondary packaging material used for the delivery and of auxiliary materials used in the production stage

Input	Amount per sprayer [g]	Distance (truck) [kg*km]	Distance (train) [kg*km]
PP	19.66*	9.20	10.60
PE	0.15*	0.17	–
LDPE	1.36*	0.80	2.63
POM	0.81*	0.24	0.73
Technical polymer	0.16*	0.049	0.16
Plastic packaging	0.034	0.00066	–
Paper and cardboard	2.52	0.050	–
Wood pallet	2.59	0.013	–
Lubricating oil	0.10	0.010	–
Electric/electronic components	0.0023	0.00011	–

*Gross mass including the plastic scrap from the injection moulding process (scrap amount reported in Table 4)

Table 3 Inventory of the production, assembly and packaging processes

Input	Amount per sprayer
Electricity for production processes	0.033 kWh
Water	47.01 g
Electricity for assembly and packaging	0.011 kWh

Table 4 Inventory of the production scrap and primary packaging wastes

Input	Amount per sprayer [g]
Plastic scrap*	0.600
Plastic packaging	0.073
Paper and cardboard	0.098
Wood pallet	0.010

*Scrap from the injection moulding process

categories as reported on the website of the international EPD system (The international EPD system 2022): global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical oxidation (PCO), abiotic depletion potential-elements (AD-E), abiotic depletion potential-fossil fuels (AD-FF), water scarcity (WS), ozone depletion potential (ODP). The specific definition of these impact categories can be found in (The international EPD system 2022).

Table 5 Main primary data of the distribution phase

Input	Amount per sprayer [kg*km]
Truck (Euro 6, 40 ton)	12.86
Ship	0.24

Life cycle inventory

This section reports the primary data used to model the processes included in the system boundaries. In particular, the main inventory data regarding the weight of all the materials used for the production of the sprayer and its distribution (Table 2), the production process (Table 3), the amount of production scrap and primary packaging wastes (Table 4), the distribution phase of the sprayer (Table 5) and the end-of-life scenarios applied to the different materials involved in the study (Table 6) are reported. Raw materials were mainly acquired from northern Europe and arrived in Italy by train; the final delivery to the production plant was performed using freight lorries (Euro 5, > 32 ton). Minor components were acquired from distributors in Italy and delivered using Euro 5 freight lorries of lower size (16–32 ton). The main component (PP) was transported using silos without the necessity of packaging. The use of auxiliary materials to the production (lubricants and electric/electronic components) has been also reported.

The Italian electricity mix has been used to model the electricity consumption. The modelling of transports for the distribution phase considered freight lorries Euro 6 of maximum size (> 32 ton) and an inland waterways ship. Since the sprayers are distributed all around Europe, European statistics have been applied to model the end-of-life scenarios of the sprayer and of the packaging. Data for all waste and wastewater treatments have been sourced from Ecoinvent v3.5 database. A distance of 50 km has been assumed for the transportation of wastes to the collection centre using a municipal collection service truck.

Regarding the study of the three variants applied to system, the following assumptions were considered:

- electricity consumption entirely covered by electricity obtained from renewable sources. Electricity mix composed of 32% hydropower, 8% photovoltaic, 23% wind power, 37% geothermal;
- substitution of POM with PP for the spring (component 10), considering a mass of 0.91 g instead of 0.81 g;
- substitution of 10.23 g of virgin PP with post-consumer PP for the production of shroud, cap and trigger. The recycled PP content over the total PP mass resulted equal to 52% (45% over the total mass of the sprayer).

Table 6 Inventory data of the end-of-life scenarios applied to each material

Material	Landfilling [%]	Incineration [%]	Recycling [%]	Reuse [%]	Source
Plastic (post-consumer resin)	27.3	41.6	31.1	–	Plastics Europe (2018)
Plastic (packaging)	20.4	38.8	40.8	–	Plastics Europe (2018)
Paper and cardboard	–	28.4	71.6	–	Confederation of European Paper Industries (2019)
Pallet	2.0	5.7	80.0	12.3	Alanya-Rosenbaum and Bergman (2020)

Table 7 Life cycle environmental impact of a trigger sprayer (traditional process)

Impact category	Unit	Contribution in absolute value			
		Upstream	Core	Downstream	Total
AP	kg SO_2 eq	1.76E−04	1.12E−04	1.93E−05	3.07E−04
EP	kg PO_4^{3-} eq	2.98E−05	3.42E−05	3.46E−05	9.86E−05
GWP	kg CO_2 eq	5.39E−02	1.98E−02	2.59E−02	9.97E−02
PCO	kg NMVOC	2.10E−04	5.90E−05	2.61E−05	2.95E−04
AD-E	kg Sb eq	4.59E−08	4.37E−08	3.90E−09	9.35E−08
AD-FF	MJ	1.59E+00	2.51E−01	4.79E−02	1.89E+00
WS	m^3 eq	3.46E−02	1.45E−02	1.76E−03	5.08E−02
ODP	Kg CFC^{-11} eq	9.84E−10	2.79E−09	5.95E−10	4.37E−09

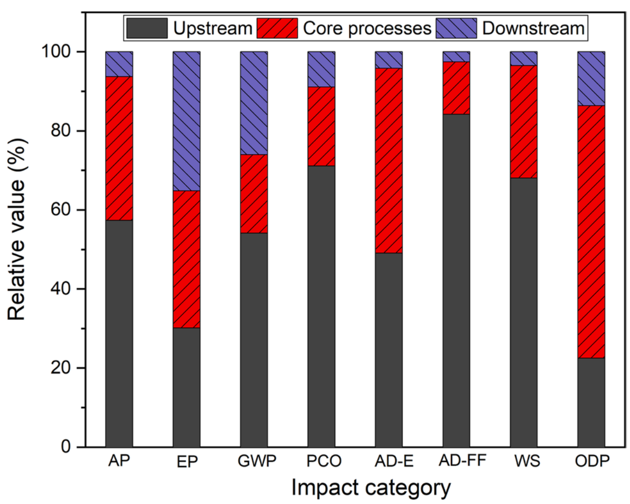

Fig. 1 Contribution of each stage to the environmental impact of the sprayer (traditional process)

The input for the electricity mix was obtained modifying an existing Ecoinvent process in order to reach the desired target in terms of energy sources. The process for recycled PP was obtained considering a sorting and remelting process adapting an existing Ecoinvent process referred to recycled polyethylene production.

Results and discussion

Life cycle impact assessment

The absolute values of the environmental impact related to the trigger sprayer, as well as the contribution of each stage considered within the analysis, are presented in Table 7 and in Fig. 1. Observing these results, it is possible to notice that the upstream stage is the life cycle stage with the highest impact (except for the category AP), mainly due to the extraction of raw materials. When considering the impact categories GWP and EP, the second stage with the highest impact is the downstream stage; in all the other categories the second highest impact is represented by the core stage. The Carbon Footprint indicator, corresponding to the impact category Global Warming Potential (GWP), is equal to 0.0997 kg CO_2 eq.

As it possible to observe from Fig. 2, three main contributors to the overall environmental impact can be identified: the polypropylene components, the electricity consumption and the end-of-life stage of the sprayer and related packaging. In the upstream stage the environmental impact is distributed among the different components according to their weight, with the major contribution related to polypropylene components and acquisition of secondary packaging material, in particular the board box used for the delivery of the sprayer. The "auxiliaries" have an important environmental impact on the category AD-E due to the use of raw materials

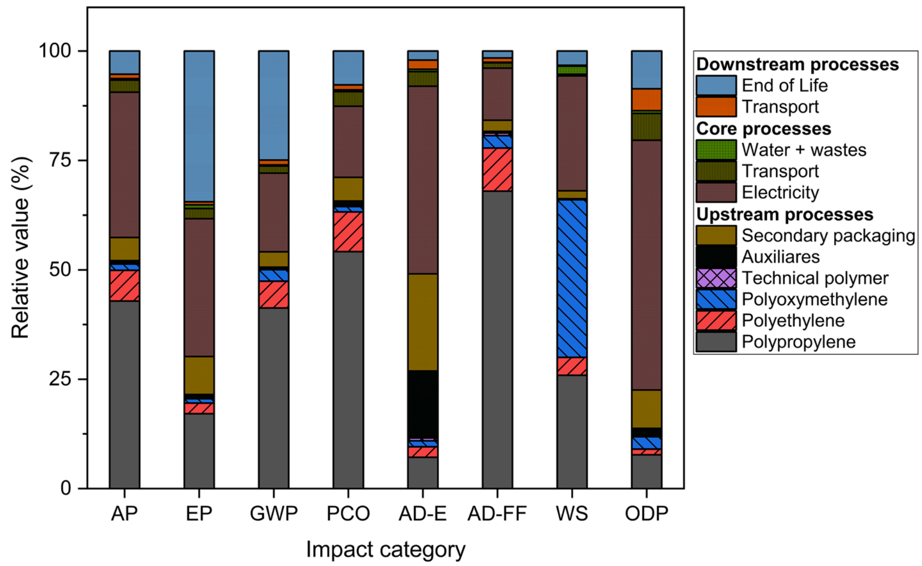

Fig. 2 Contribution of each process/material to the environmental impact of the sprayer (traditional process)

Table 8 Life cycle environmental impact of a trigger sprayer after the implementation of the three proposed variants

Impact category	Unit	Contribution in absolute value			Variation (%)	
		Upstream	Core	Downstream	Total	Total
AP	kg SO_2 eq	1.70E−04	1.77E−05	1.92E−05	2.07E−04	−32.6
EP	kg PO_4^{3-} eq	2.12E−05	6.55E−06	3.45E−05	6.23E−05	−36.8
GWP	kg CO_2 eq	4.80E−02	3.25E−03	2.58E−02	7.71E−02	−22.7
PCO	kg NMVOC	2.11E−04	1.49E−05	2.61E−05	2.52E−04	−14.6
AD-E	kg Sb eq	2.80E−08	1.55E−08	3.89E−09	4.75E−08	−49.2
AD-FF	MJ	1.50E+00	4.16E−02	4.78E−02	1.59E+00	−15.9
WS	m^3 eq	1.44E−02	3.04E−03	1.75E−03	1.92E−02	−62.2
ODP	Kg CFC^{-11} eq	5.65E−10	4.38E−10	5.94E−10	1.60E−09	−63.4

for the production of electric components. Polyoxymethylene has a predominant environmental impact on the category WS, due to the water consumption required for the synthesis of the polymer (700 g for 1 kg of polymer) (Kalbusch and Ghisi 2016). The main contribution to the core stage is caused by the electricity consumption that covers around 80% of the overall impact for each category in this stage. In the downstream stage, the environmental impact is mainly caused by the end-of-life of wastes, with exception of the AD-E impact category, in which transports are the main contributor. The contribution of the waste treatment is mainly determined by the incineration process, with exception of the impact category EP in which landfilling operations cause almost the entire contribution.

The results obtained by the application of the three implementations are presented in Table 8 and Fig. 3. With respect to the reference sprayer, there is a general decrease of the total contribution for each impact category. In particular the GWP is decreased of around 23% and the AD-FF of around

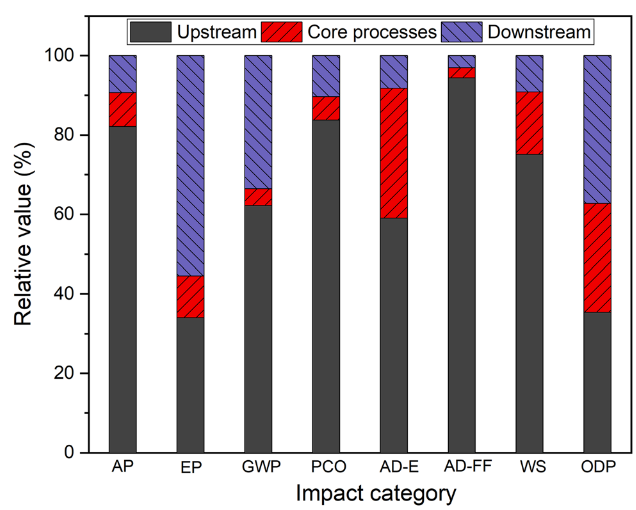

Fig. 3 Contribution of each stage to the environmental impact of the modified sprayer

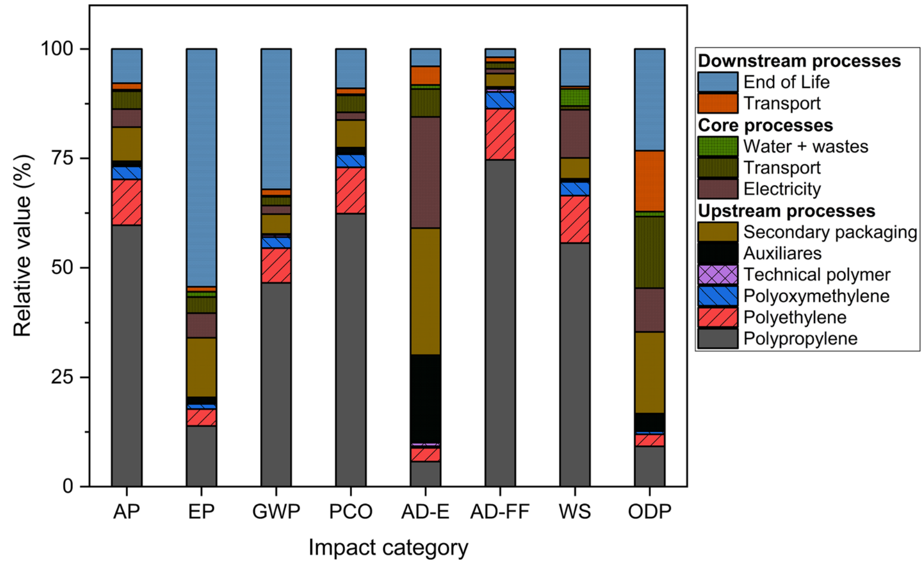

Fig. 4 Contribution of each process/material to the environmental impact of the modified sprayer

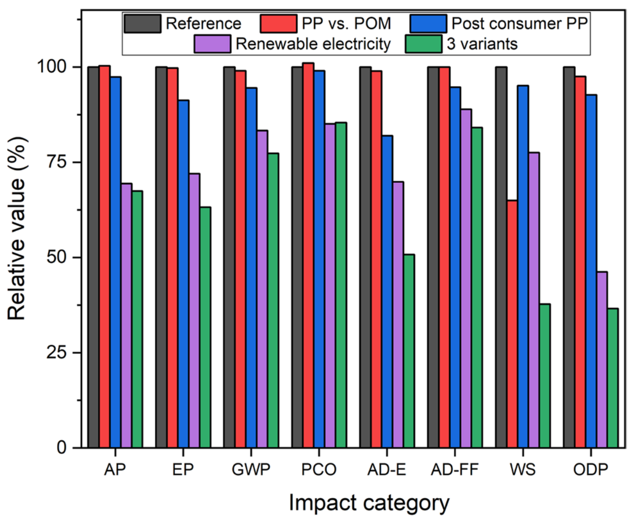

Fig. 5 Comparison between the environmental impact of the reference sprayer and of the modified one

16%. Moreover, the impact of the core process strongly decreases for each impact category due to the use of renewable resources for electricity production. In this analysis, the main contributor to the environmental impact of the sprayer is even more markedly the upstream stage.

As it is possible to observe from Fig. 4, the contribution of the electricity consumption to the overall environmental impact of this sprayer is decreased of around 40% in several categories (AP, EP, GWP, PCO, AD-FF, ODP), around 20% in WS and 10% in AD-E. Interestingly, the decrease in electricity contribution for manufacturing reveals that the transport operations of the raw materials to the production plant become the main contributors to the environmental impact of the core stage. Moreover, the main contributors of the modified sprayer are the polypropylene and polyethylene components and the end-of-life stage. It should be also noticed that, in the upstream stage, the role of secondary packaging and auxiliary materials gains importance due to the reduced impact of the components produced using recycled material.

From the comparison of the three proposed variants, shown in Fig. 5, it can be observed that the substitution of POM with PP for the spring production (PP vs POM) has a negligible contribution on the reduction of the environmental impact of the sprayer due to the higher weight of the PP spring in comparison to the POM spring, that vanishes almost all the benefits. The main positive effect regards the reduction of the WS impact that is as high as 35% due to the lower water consumption involved in the polypropylene production process. However, it should be considered that the substitution of POM with PP decreases the number of different polymers used for the production of the sprayer (the other ones are PE and a technical polymer), with a consequent relevant facilitation of sorting and recycling operations in the waste treatment phase (Stein 1992; Lange 2021). The use of recycled PP material instead of the virgin one (post-consumer PP) allows a modest reduction of the total contributions for each impact category: AP—3%, EP—9%, GWP—5%, PCO—1%, AD-E—18%, AD-FF—5%, WS—5%, ODP—7%. The use of renewable resources (renewable electricity) allows a strong decrease in the total contribution for each impact category: AP—30%, EP—28%, GWP—16%, PCO—15%, AD-E—30%, AD-FF—11%, WS—22%, ODP—54%. The combination of the three proposed variants (3 variants) leads to very good and promising results: AP—33%, EP—37%, GWP—23%, PCO—15%, AD-E—49%, AD-FF—16%, WS—62%, ODP—63%.

Discussion

In order to further improve the environmental performance of this product, a twofold strategy should be followed: on one side the implementation of technologies able to produce equivalent components using only recycled materials and, on the other side-closely linked to the first one-the enhancement of a sorting and recycling supply chain able to provide high-quality recycled polymers. Moreover, the attention should be also focused on the reduction of the amount of secondary packaging material used for the delivery, since its impact is quite relevant. From the perspective of the Circular Economy Action Plan promoted by the EU within the European Green Deal, it seems essential the promotion of sustainability in order to maintain the values of products as long as possible (European Commission 2010, European Commission 2018, European Commission 2020). The implementation of further upgrades to the production process (i.e., use of recycled material), to the end-of-life of plastic wastes (i.e. improve sorting and recycling) or the growth of circular economy with the possibility of reusing plastic sprayers multiple times (each sprayer is designed for 5 l of dispensed volume while they are usually used to dispense the volume of a single bottle of 0.5–1 l) could allow further reduction of the environmental performances of these products.

Conclusion

In this study, primary data were used for the evaluation of the environmental performances of a commercial plastic sprayer for household cleaning. Moreover, a comparison with an improved sprayer in which some components were produced using recycled polypropylene, the polyoxymethylene spring was substituted with a polypropylene one and the electricity for the production process was obtained only from renewable resources was also performed. Results show that the impacts of the commercial sprayer are mainly caused by the upstream stage due to the extraction of raw materials, followed by the core stage (due to electricity consumption) and by the downstream stage (due to the end-of-life of the sprayer). The application of the three improvements to the system leads to a general and considerable decrease in all the impact categories, mainly driven by the use of renewable resources for the electricity production (GWP—16%), followed by the use of recycled polypropylene (GWP—5%) and only for few categories by the substitution of polyoxymethylene with polypropylene (GWP—2%). Applying simultaneously the proposed modifications, the carbon footprint of the plastic sprayer can be decreased from 0.0997 kg CO_2 eq to 0.0771 kg CO_2 eq, with a reduction of around 23%. Referring to the annual production of the analysed sprayer, accounting of around 15 million pieces, the implementation of the proposed modifications would result in the reduction of 339 ton of CO_2 eq emissions and of 4500 GJ of used fossil resources.

Author contributions FV contributed to conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing-original draft preparation; AD contributed to supervision, writing-review & editing, funding acquisition.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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