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Environmental impacts of food packaging: Is it all a matter of raw materials?

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A R T I C L E I N F O

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A B S T R A C T

The packaging sector and the environmental impacts stemming from its various materials and applications are currently at the forefront of scientific and political debate. To estimate the environmental impacts associated with raw materials and identify the role of industrial processes, this study presents a cradle-to-grave Life Cycle Assessment applied to two distinct packaging formulations for chocolate bars, namely oriented polypropylene-based and paper-based packaging. The product systems related to the two alternatives were compared by focusing on the contribution of each resource input and emission of the production phase, to identify respective environmental trade-offs and potentials for future improvements throughout the life cycle. Our study also proposes a laboratory-based approach to develop robust assumptions concerning the modeling of end-of-life material treatment and provide support to decision-making toward environmentally sustainable waste management practices. From the outcomes, a relative preference emerges for paper-based packaging, from a minimum of 10 to a maximum of 16 out of 18 environmental categories, depending on the evaluated scenario. The hotspot analysis highlighted a significant influence of the processing phases, with raw materials being generally characterized by lower percentage contributions to the final impact. In conclusion, the findings underscore the importance of considering the entire life cycle when assessing packaging sustainability. Moreover, the proposed laboratory approach offers valuable insights for policymakers and industry stakeholders to optimize end-of-life strategies and minimize the overall environmental footprint of packaging materials.

1. Introduction

Food production and consumption have increased in recent years as a consequence of accelerating urbanization and globalization, both of which induced more complex and longer food chains (WHO, 2015; Zhang et al., 2022). An increasing food demand also drives the growth of the sectors related to food production such as the packaging industry, which is considered one of the main actors in the food value chain (Zhang et al., 2022). The packaging industry, indeed, already generates approximately 2 % of the gross national product in developed countries, and about half of the total amount is produced for food (Robertson, 2020; Vignali, 2016). Moreover, with a global 5 % annual growth rate, the consumption of packaged foods is expected to increase from $1.9 trillion in 2020 to $3.4 trillion by 2030 (Kan and Miller, 2022; Kumar

Abbreviations: EOFP, Ozone formation potential (ecosystem); EoL, End of life; EU, European; EWC, Estimated waste composition; FEP, Freshwater eutrophication potential; FETP, Freshwater ecotoxicity potential; FFP, Fossil resources scarcity; FU, Functional unit; GHG, Greenhouse gasses; GWP, Global warming Potential; HOFP, Ozone formation potential (human health); HTPc, Human carcinogenic toxicity potential; HTPnc, Human non carcinogenic toxicity potential; IRP, Ionizing radiation potential; LCA, Life cycle assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; LOP, Land use occupation; MEP, Marine eutrophication potential; METP, Marine ecotoxicity potential; ODP, Ozone depletion potential; OPP, Oriented polypropylene; OPPmet, Metallized polypropylene; OPPb, Oriented polypropylene-based packaging; PB, Paper-based; PBp, Paper-based packaging; pcs, Pieces; PL, Polish; PLSSpo, Printing, lamination, cold seal application, and slittering process operations; PWC, Proxy waste composition; SOP, Mineral resources scarcity; SS, Single score; TAP, Terrestrial acidification potential; TETP, Terrestrial ecotoxicity potential; WCP, Water consumption potential; WtE, Waste to Energy.

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and Dwshmukh, 2021).

Packaging is essential to prevent the deterioration in the quality and safety of foods and beverages during distribution, sales, and consumption (Mihindukulasuriya and Lim, 2014; Sasaki et al., 2022; White and Lockyer, 2020), to extend the shelf-life of foods (Carocho et al., 2015) and contribute to minimizing food waste (Narayanan et al., 2017; Ribeiro-Santos et al., 2017), and to provide useful information to consumers regarding, for instance, ingredients, fact sheets, storage conditions, and the environmental performance of the product (Han et al., 2018; Kan and Miller, 2022; Singh et al., 2016). Packaging materials vary in nature but polymers such as PET or polyolefins have been historically predominant in the market (Silvestre et al., 2011), thanks to their desirable characteristics of fine-tunable mechanical, thermal, and corrosion-resistant properties, light-weighting properties, well-established and cost-effective production processes (Gupta, 2011; Narayanan et al., 2017; Sathiya Prabhakaran et al., 2020; Zhang et al., 2022). Consequently, packaging is among the main end-use application sectors of plastics, accounting for >150 Mt./y (40 % of the total plastic uses) (Geyer et al., 2017; ING Economics Department, 2019) and so contributing to the annual global plastic production which increased sharply from 2 to 381 Mt./y since 1950 (European Environment Agency, 2023). However, severe concerns about the environmental implications of plastic production, consumption, and inefficient management at end-of-life (EoL) have raised over time and also affected plastic-based food packaging (Haward, 2018; Mangaraj et al., 2019). Some of the main drawbacks are related to the depletion of natural resources, greenhouse gas (GHGs) emissions into the atmosphere (Hopewell et al., 2009; Kan and Miller, 2022), water and energy consumption, and relative long persistence in the ecosystem (Deshwal et al., 2019; Kan and Miller, 2022). Furthermore, in recent years, there has been significant growing attention regarding the presence of microplastics in the environment (Coralli et al., 2022; Corella-Puertas et al., 2023), as we further comment in the section 2. In addition to these issues, the use of packaging often requires further material and energy supply inputs for cutting, printing, adhesive application, and similar additional operations, which are seldom considered in LCA and debates relating to the environmental impacts of packaging.

To this aim, in this study, we applied the Life Cycle Assessment (LCA) to compare the environmental performance of two packaging alternatives (i.e., plastic-based packaging and paper-based packaging) concerning the same function. The proposed comparison is not thought to provide a definitive preference between paper and plastic packaging, but rather to discuss the issues related to the whole life-cycle of packaging by considering multiple facets into the debate, such as the role of raw material processing, the potentially achievable environmental advantages or disadvantages across the analyzed categories and also the mass of the material (in the Functional Unit definition, FU). Incorporating all these variables is expected to enhance the awareness in the public debate and the support to relevant stakeholders about the most critical aspects related to these food packaging materials.

KB Folie Polska sp.z. o.o. (KB Folie Polska Sp.z o.o., 2023), later KB Folie, is a Polish company involved in the design and production of

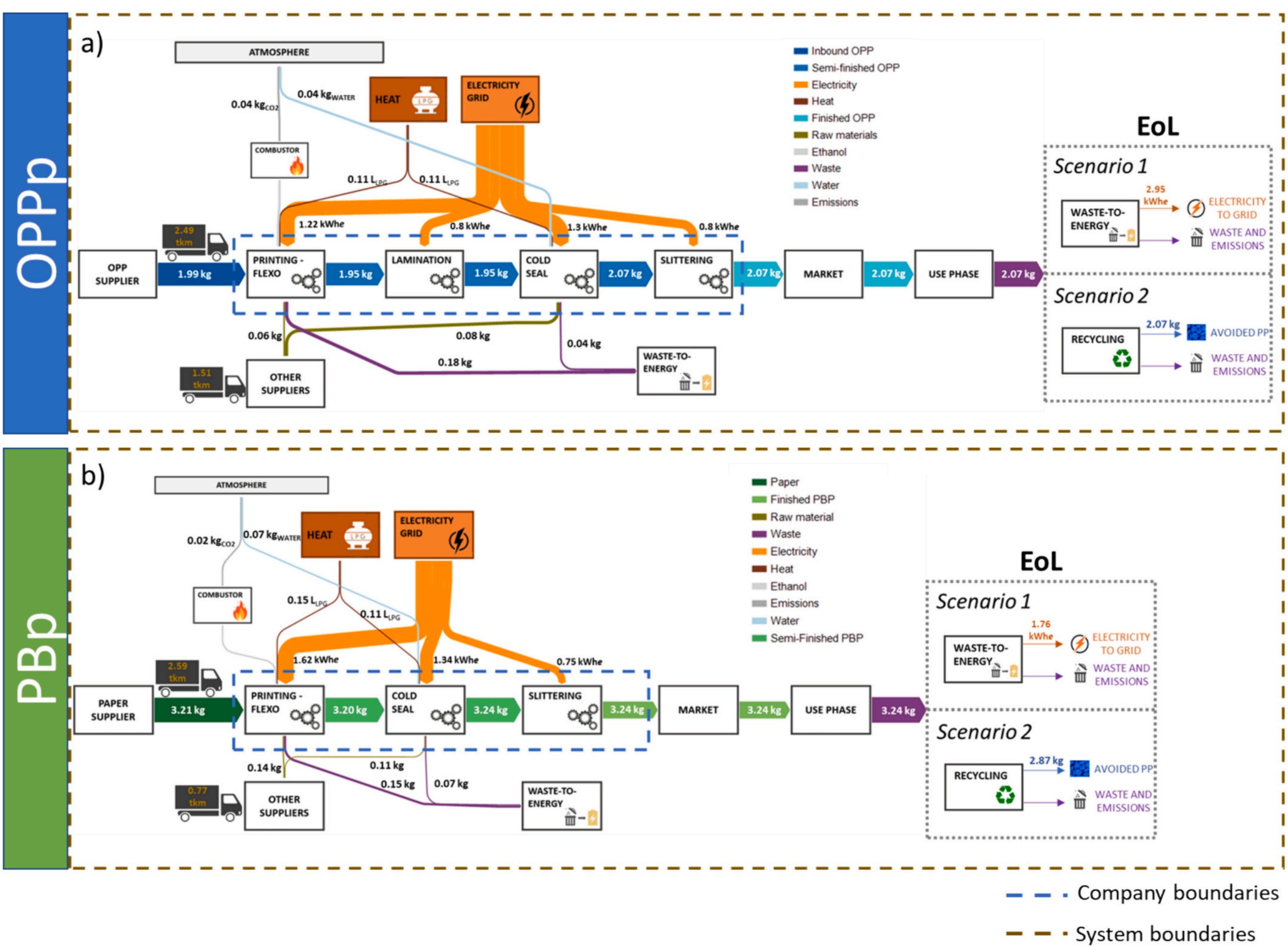

Fig. 1. Representation of a) Oriented polypropylene based packaging (OPPb) product system and b) Paper based packaging (PBp) product system. The two compared scenarios represent two different alternatives of End-of-Life (EoL) management (i.e., waste-to-energy and recycling).

packaging formulation and it was selected as a case study for system investigation. The company production system applies printing, lamination, cold seal application, and slittering process operations (PLSSpo) to oriented polypropylene (OPP) and printing, cold sealing, and slittering operations to paper-based (PB) inbound layers (Fig. 1). For both formulations, the acronym PLSSpo will be used to refer to the manufacturing phase. The sequence of processes is adequate to both the packaging object of study, i.e., the traditional OPP packaging (OPPb) formulation, composed of about 90%*w*/w of oriented polypropylene; and the alternative, constituted by PB (paper fraction ≅ 95%*w*/w). The list and description of flows involved in the two product systems are reported in section 3.2. Beyond sustainability purposes, both OPPb and PB packaging (PBp) ensure the preservation of the technical requirements and needs of the food industry. The evaluation of an existing system allowed to work on primary data related to the packaging processing phase, filling the previously described literature gap.

2. Literature review

The interest in food packaging sustainability is demonstrated by a growing number of studies relevant to this topic in recent years. In particular, there has been a significant increase in studies applying LCA (ISO, 2006a, 2006b) to several types of food packaging products (Bishop et al., 2021; Boone et al., 2023; Casson et al., 2022). However, LCA direct comparisons between plastic-based and paper-based packaging have been proposed only in a few cases (Delahaye et al., 2023; Zabaniotou and Kassidi, 2003), with usually a marginally better environmental performance for paper packaging (Sokolova et al., 2023), although a clear preference has not emerged. Furthermore, for both plastic and paper, particular attention has been given to the impacts associated with raw materials and recycling potential, but there is a gap of information related to the processing and material finalization phases (Bousquin et al., 2011). Missing primary and secondary data related to sector-specific industrial processes often hinders the creation of representative LCA models.

2.1. End of Life management of plastic packaging

The short lifespan of packaging materials, together with their large volumes to be treated after use, create significant issues, especially when plastics are not properly collected at EoL or undergo landfilling or terrestrial and marine littering (Barnes et al., 2009; Sorrentino et al., 2007). In particular, the latter was estimated to enter from 4 to 12 Mt. of plastic waste into marine ecosystems in 2010 (Jambeck et al., 2015). Synthetic fibers contamination of freshwater systems and terrestrial habitats is also increasingly reported (Dris et al., 2017; Wagner et al., 2014; Zubris and Richards, 2005). To solve this issue, several Eco-design approaches (e.g., recyclable by design) are gaining increasing interest (Williams and Georgina, 2021). However, it is estimated that, of the seven billion tons of plastic waste produced globally, only 10 % are effectively recycled (Shan et al., 2023), with the rest being nonfunctionally recovered, lost, or disposed of. Such a low rate might be due to several reasons including issues of setting proper collection strategies, often inadequately regulated especially in poor and developing countries (Kibria et al., 2023), severe contamination by different materials contained in the waste plastic fraction that generally requires the development of efficient sorting and separation technologies (Nanda et al., 2023), relatively high temperature and pressure conditions during recycling. Ultimately, these reasons affect technical and economic feasibility of plastic packaging recycling, particularly for flexible films and multi-material packaging (e.g., materials identified with the #7 and classified as “other”) (Kibria et al., 2023) and stimulated the research toward new and more sustainable alternatives such as biodegradable biopolymers (Attaran et al., 2017; Siracusa et al., 2011; Souza and Fernando, 2016) and paper-based materials.

2.2. Paper packaging

Paper is likely the oldest material used for food product packaging. Since the year 2000, approximately 47 % of total paper and paperboard produced was used for packaging applications (Deshwal et al., 2019) and nowadays this market represents about 31 % of the global market segment (Hillier et al., 2017). Although paper is a main solution for the food packaging industry, some controversial aspects are still under debate. According to Deshwal et al. (2019), plain paper may not be sufficient to preserve and protect food products adequately because of its high permeability to oxygen and moisture, low heat weldability, and strength. Very often, it is necessary to impregnate or coat paper with some additives or combine it with layers made of aluminum or plastic to achieve the desired properties of the packaging material, while reducing its recyclability at EoL. In 2022, about 414 million tons of paper were produced, of which about 265 million tons (i.e., 64 %) were destined for the packaging sector. Packaging paper is also responsible for almost 29 % of the world's harvested industrial wood (Bousquin et al., 2011) and, in addition, the industry of pulp and paper, probably also because of its high contribution to the global gross domestic product, is considered of environmental concern (Deshwal et al., 2019). Therefore, innovations in food packaging systems are driven by a dual effort aimed at *i)* meeting the evolving needs of the market, such as consumers' preference for long-lasting and high-quality food productswhile *ii)* reducing the environmental impacts (Han et al., 2018).

3. Methods

LCA is a methodology standardized by ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a, 2006b) and it is structured on four interconnected phases: *i)* Goal and scope definition; *ii)* Life Cycle Inventory (LCI); *iii)* Life Cycle Impact Assessment; and *iv)* Interpretation.

3.1. Goal and scope definition

The main goals of this study are: *i)* to evaluate and compare the environmental performances of the oriented polypropylene packaging (OPPb) and paper-based packaging (PBp) product systems designed to pack 100 g chocolate bars with the same characteristics of food protection and preservation; *ii)* estimate the effective contribution of the PLSSpo and the EoL management on the total environmental impacts of the packaging life cycle; *iii)* to fill the information gap in the relevant literature about PLSSpo in order to increase the awareness about the packaging manufacturing phase; and *iv)* to compare recycling and waste-to-energy (WtE) strategies as different EoL treatments and determine the contribution of this stage to the cumulative impacts. This study is designed to provide site-specific results, which are then extended to the European context through the application of a sensitivity analysis. The comparison between the environmental performance of the two packaging solutions is provided by referring to a real and currently active system, developed by the Polish company KB Folie. Results are reported according to the ReCiPe 2016 Life Cycle Impact Assessment (LCIA) method v. 1.08, perspective (H) (Huijbregts et al., 2017). ReCiPe 2016 provides a comprehensive estimation of the interactions between the system under scrutiny and the environment for a set of 18 midpoint categories, namely: GWP, Global warming (kg CO_2 eq); ODP, Stratospheric ozone depletion (kg CFC11 eq); IRP, Ionizing radiation (kBq Co-60 eq); HOFP, Ozone formation-human health (kg NOx eq); PMFP, Fine particulate matter formation (kg PM 2.5 eq); EOFP, Ozone formation Terrestrial ecosystems kg NOx eq); TAP, Terrestrial acidification (kg SO_2 eq); FEP, Freshwater eutrophic. (kg P eq); MEP, Marine eutrophic. (kg N eq); TETP, Terrestrial ecotoxicity (kg 1,4-DCB eq); FETP, Freshwater ecotoxicity (kg 1,4-DCB eq); METP, Marine ecotoxicity (kg 1,4-DCB eq); HTPc, Human carcinogenic toxicity (kg 1,4-DCB eq); HTPnc, Human non-carcinogenic toxicity (kg 1,4-DCB eq); LOP, Land use occupation (m^2a crop eq); SOP, Mineral resource scarcity (kg Cu eq); FFP, Fossil resource scarcity (kg oil eq); WCP, Water consumption (m^3); and the Single Score (ISO, 2006b). The Single Score is calculated in accordance with the ReCiPe 2016 methodology, by summing the three endpoint categories: Human Health, Ecosystem, and Resources, once normalized to the unit of measurement (pts), in relation to the hierarchical perspective. The three categories were calculated through the grouping and weighting procedures outlined in the ReCiPe 2016 methodology, using the Simapro software.

No allocation criteria were applied in the study and, according to ISO 14044:2006 (ISO, 2006b) it has been preferred to apply system expansion to include advantages and disadvantages associated with multi-functional processes.

The system boundaries of the models are depicted in Fig. 1 with gold dashed lines and include, *i)* extraction, production, and supply of raw materials and intermediates involved in the production; *ii)* generation, supply, and consumption of the energy carriers (e.g., electricity from grid and heat from liquid petroleum gas- LPG- fuel); *iii)* operative phases; *iv)* the EoL management of waste generated within the company boundaries and in the post-use phase, following a cradle-to-grave approach. The use phase is considered to be the same for both packaging materials and not to contribute to the final impacts significantly: therefore, it was left out of scope in virtue of a cut-off criterion. This one was the only cut-off applied to the study. In the same way, the contribution of the PLSSpo infrastructure is not considered in the study, since negligible thanks to its relatively long life span. Since the weight of a single chocolate bar packaging is dependent on the material employed (OPPb or PBp), the chosen FU is the amount of packaging material needed to pack 1000 pieces (pcs) of 18 cm × 16 cm chocolate bars of 100 g weight each. The software employed for the modeling and calculations is SimaPro 9.5 (PRé Consultants, 2022).

3.2. Life Cycle Inventory (LCI)

In this phase, the product system models are created and populated with data related to material and energy flow inventories to provide an accurate and representative system network of the processes involved all over the OPPb and PBp life cycle.

3.2.1. Assumptions and common aspects

The product systems of OPPb packaging and PBp packaging are depicted in Fig. 1, with dashed lines representing, respectively, the LCA system boundaries in gold and the company boundaries in blue. Most of the foreground processes are compiled with primary data directly provided by the company (e.g., the amounts of materials used, energy flows, generated waste, and emissions). The whole inventory is reported in Table S1 of the supplementary information (SI). When primary data were not available, own calculations and estimations were assumed based on literature data and the ecoinvent 3.9 database (Wernet et al., 2016) (proxy processes were listed in Tables S2 and S3). The selected ecoinvent approach for secondary processes was "At Point Of Substitution" (APOS). In APOS, in the case of direct or indirect involvement of secondary materials in the product system, whether they be by-products or waste, a fraction of the impacts related to their previous life cycle as well as the impact of the treatment process applied are included based on economic allocation (Wernet et al., 2016). We believe this approach may provide good representativeness of the European packaging sector, in which secondary materials constitute a relevant part of the inflow to manufacturing (European Union, 2022). In contrast, the "cut-off" approach would have excluded all the burdens and benefits relating with the use of secondary materials, while the "consequential" approach would have required knowledge of processes out of the scope of this study and for which reliable information was not at our reach. The assumptions are summarized below:

1. Inbound OPP and paper are purchased by external suppliers, who provide the inventory of the electricity consumed in the manufacturing phase of the semi-finished layers (1.93 kWh/kg for OPP and 0.92 kWh/kg for paper). The impact of electricity consumption associated with semi-finished OPP and paper was estimated by modeling on SimaPro the Polish electricity mix, according to the most recent data reported in IEA (2022). Then, the impact of raw OPP and raw paper is estimated by referring to the polypropylene granulate and kraft paper ecoinvent processes (Wernet et al., 2016). The total impacts of the inbound semi-finished OPP and paper are finally calculated as a linear combination of the raw material impact (drawn on ecoinvent) plus the electricity consumption impact (drawn from the supplier information).
2. Electricity flows associated with the PLSSpo were calculated in consistency with the annual final energy consumption of the company, which was normalized to the FU. Also, in this case, the Polish electricity mix was taken as the reference process.
3. LPG flows are based on the annual consumption of the company, further normalized to the FU. The emissions associated with in-site combustion are calculated by referring to EPA (2017).
4. According to primary information, the inks are assumed to be composed of nitrocellulose (30 %) and ethanol (70 %); the cold seal is considered to be composed of water (50 %) and latex (50 %); the adhesive is assumed to be constituted by methyl-diphenyl-diisocyanate (60 %) and polyols (40 %) with a molecular weight between 500 and 2000 g/mol.
5. No primary data related to EoL management were available. Therefore, we developed two alternative scenarios to provide a broader spectrum of possible EoL treatments, including *i)* mechanical recycling (Scenario 1) and *ii)* WtE (Scenario 2). The amount of energy recovered by the WtE treatment, which is given credit for avoiding the generation of the same amount of final energy from the national electricity grid mix, is estimated from the lower heating values (LHV) of the materials, determined through experiments based on the Mahler's Bomb. The disposal of residues from the WtE processes is modeled considering quantitative analysis results for the content of ash and metals. The laboratory tests were carried out in the University of Bologna laboratories and more details about the EoL assumptions are reported in sections 3.2.4 and 3.2.5.
6. The management of the waste generated inside the company boundaries was modeled according to scenario 2 (section 3.2.5).
7. The distances covered using transportation (i.e., freight lorries) to supply the inlet raw materials and semi-finished layers were provided by the company and are summarized in Table 1.
8. The distance between the company and the recycling and WtE plants was approximately estimated in 100 km.

3.2.2. Oriented polypropylene-based packaging formulation

The product system consists of 4 stages: printing, lamination, cold seal application, and slittering (Fig. 1a). The OPP semi-finished layers are provided by an external supplier. In the printing stage, 0.12 kg/FU of ink are applied. The ethanol fraction evaporates completely during the printing process: the gaseous emissions (0.17 kg/FU) are burned into a combustor and assumed to be mainly converted to CO_2 before being

Table 1
distances traveled by oriented polypropylene (OPPb), metalized oriented polypropylene (OPPmet), paper, adhesives, inks, cold seal, and material sent to the End-of-Life (EoL) scenario from suppliers to the company and computed tkm.

Truck	Distance (km)	tkm/FU (OPPb)	tkm/FU (PBp)
OPP	1100	2.28	/
OPPmet	100	0.21	/
Paper	1250	/	2.59
Adhesive	360	0.75	/
Inks	10	0.02	0.021
Cold seal	360	0.75	0.75
EoL	100	0.23	0.35

released into the atmosphere. The amount of emitted CO_2 is estimated according to stoichiometry. The printing process requires 1.20 kWh$_e$/FU of electricity and 1.10 L/FU of LPG. Due to process inefficiencies, 0.12 kg/FU of inbound solid material is not introduced in the product and it is sent to the WtE management. The 1.95 kg/FU of printed layers are directed to the lamination stage, which requires 0.80 kWh$_e$/FU. Then, 0.08 kg/FU of cold seal and 0.10 kg/FU of adhesives are applied to the layers. In the cold sealing stage, 0.04 kg/FU of water is evaporated and emitted into the atmosphere. The cold sealing phase requires 1.30 kWh$_e$/FU, 0.11 L/FU of LPG, and generates 0.10 kg/FU of waste. The resulting mass of 2.13 kg/FU of materials is conveyed to the slittering stage (0.80 kWh$_e$) and finalized for shipment to the market.

3.2.3. Paper based packaging formulation

The PBp production system consists of 3 stages: printing, cold seal application, and slittering (Fig. 1b). The PBp layers are provided by an external supplier. 3.21 kg PBp/FU is sent to the printer, where 0.14 kg ink/FU of ink is applied, employing 1.63 kWh$_e$/FU and 0.15 L/FU of LPG. In this stage, 0.25 kg/FU of waste is generated and 0.19 kg/FU of ethanol is evaporated and sent to the combustor. The amount of emitted CO_2 is also in this case estimated according to stoichiometry. The lamination stage does not occur for the PBp layers so 3.08 kg/FU of printed layers are directly conveyed to cold seal application, where 0.11 kg/FU of cold seal are applied. The energy demand for cold seal application is 1.34 kWh$_e$/FU and 0.11 L/FU of LPG. The amount of waste generated is estimated at 0.07 kg/FU and the evaporated water is emitted into the atmosphere. After the slittering process, which consumes 0.75 kWh$_e$/FU, 3.12 kg/FU of packaging materials are obtained. Comprehensively, PBp is characterized by a lower electricity consumption concerning OPPb (approximately, −10 %) and by a lower amount of raw materials since adhesives are not required in PBp formulation.

3.2.4. Recycling inventories

Recycling aims to convert wasted materials into valuable products. Since it was not possible to reproduce a recycling system based on primary data, it was decided to refer to inventories available in the literature to estimate the potential environmental impacts and credits of recycling, i.e., De Feo et al. (2015) for PBp and Shan et al. (2023) for OPPb. The inventories of the two recycling systems, reported in Table S4 and S5 in the Supplementary Information, have been reproduced in SimaPro and integrated into the LCA model. In particular, for plastic, it was decided to model a mechanical recycling process, mainly because of its higher diffusion and the absence of reported data related to chemical recycling inventories (Caelli et al., 2024; Rizos et al., 2023). Assuming a 100 % efficiency of the recycling process, 4.17 kg/FU of polypropylene granulate at a low grade and 6.54 kg/FU of recycled paper were obtained by recycling the 1000 pcs of both OPPb and PBp and credited in the LCA model as avoided products. The credit associated with the avoided products is drawn from ecoinvent (Wernet et al., 2016).

3.2.5. Waste to energy inventories

The main references for emissions and burdens associated with waste OPPb and PBp were the two ecoinvent processes "*Waste polypropylene {CH}| treatment of waste OPP, municipal incineration with fly ash extraction*" and packaging paper "*Waste paper {CH}| treatment of waste paper, municipal incineration with fly ash extraction*". The two processes have been integrated by replacing the amount of electricity recovered and incineration residues with data calculated as reported in the following sections 3.2.5.1 and 3.2.5.2.

3.2.5.1. Lower heating values. The LHV of OPPb and PBp are calculated according to ISO 1928:2020 (ISO, 2020) using a Mahler Bomb, which is typically employed to evaluate whether waste materials are suitable for WtE treatments (Amen et al., 2021; Boumanchar et al., 2017; Kathiravale et al., 2003). The system was calibrated using benzoic acid. The LHVs for OPPb and PBp were estimated at 47.18 MJ/kg and 21.99 MJ/kg, respectively. According to the above mentioned LHV values and the ecoinvent database, which reports a transformation efficiency of 12.3 % for the OPPb proxy process and 12.8 % for the PBp proxy process (Wernet et al., 2016), the electricity potentially generated by WtE treatment of the EoL materials was estimated as 4.21 MJ/kg (OPPb) and 1.74 MJ/kg (PBp) and included in the model as an avoided product.

3.2.5.2. Content determination of residual ash and metals. Ash content was estimated to estimate the amount of WtE solid residue. The estimation is provided by heating the OPPb and PBp samples in muffle according to ISO 21656:2021 guidelines (ISO, 2021).

The quantitative analysis of metals is performed by performing acid digestion on 0.21 g of ashes derived by calcination of OPPb at 815 °C and on 0.52 g of non-calcinated PBp using the Advanced Microwave Digestion System ETHOS EASY. The ramp temperature was set to reach 200 °C in 15 min and then maintained for 15 min more. The digestion mixtures employed for OPPb and PBp were 2 mL HNO_3 (65 %) and 8 mL HCl conc (37 %) for the former one, and 9 mL HNO_3 conc (65 %) and 1 mL H_2O_2 (30 %) for the latter one, respectively. Reagents employed were suprapure. Once digestions were completed, solutions were loaded into a flask and added with 0.2 % HNO_3 solution to the final volume of 50 mL. Solutions were then filtered with "filtra 589^3 ashless". Before and after filtration, the filter was dried in an oven at 105 °C for 2 h and weighed. Digested solutions were finally analyzed utilizing MP-AES. At first, the digested solutions were analyzed without standards at the emission wavelengths of Sb, Pb, Ni, Zr, Cd, As, Hg, Tl, V, Cr, Zr, Ti, and Al to perform a qualitative screening of the present elements. This preliminary screening allowed us to identify the potential presence of V, Cr, Zr, and especially Ti e Al. With the same screening the presence of Sb, Pb, Ni, Zr, Cd, As, Hg, and Tl in the sample was excluded. For this reason, for V, Cr, Zr, Ti, and Al dedicated standards were prepared.

According to the obtained concentration of ash and metals, the ecoinvent processes "*Waste polypropylene {CH}| treatment of waste OPP, municipal incineration with fly ash extraction" and "Waste paper {CH}| treatment of waste paper, municipal incineration with fly ash extraction*" were properly modified by replacing the reported amount of ash and metals with the empirically estimated ones (see Section 4.1).

3.3. Life Cycle Impact Assessment

In the LCIA phase, material and energy flows identified and quantified LCI (e.g., direct and indirect emissions, energy and resources consumptions, etc.) are converted into potential environmental impacts using well-established cause-effect models. In our analysis, the ReCiPe 2016 impact assessment method (Huijbregts et al., 2017) was applied. ReCiPe 2016 allows the investigation of a wide spectrum of environmental categories, avoiding the problem of burden shifting and the greenwashing phenomena. In addition to this, the choice was driven by the following reasons: first the existence of previous publications in which the same method was selected (Accorsi et al., 2022; Lewis et al., 2024; Vitale et al., 2018; Yadav et al., 2024) and, second, the fully transparent characterization, normalization and weighting mechanisms from midpoint to endpoint results. The list of the categories included in the method are reported in the Goal and Scope (section 3.1).

3.4. Sensitivity and uncertainty analysis

The outcomes of the contribution analysis were taken as the reference for setting sensitivity analysis, performed to test the robustness of the model created and enable identification and quantification of the influence of the main exogenous parameters on the environmental impact of the entire system (Goedkoop et al., 2016).

Furthermore, uncertainty evaluation and propagation were performed both for midpoint and endpoint categories by employing the pedigree data quality matrix (Weidema and Wesnæs, 1996). More details about data uncertainty are reported in Table S6. As commented earlier, primary data provided by the company were mainly used for the LCA. As such, data related to the PLSSpo are considered very reliable and characterized by the highest scores for data quality criteria commonly applied in LCA such as, for instance, geographical, temporal, and technological representativeness. Conversely, since recycling was modeled according to literature datasets, lower data quality scores were assigned to the input data.

4. Results and discussions

4.1. Lower heating values, ash, and metal contents

The estimated LHV of OPPb and PBp were 47.18 MJ/kg and 21.99 MJ/kg respectively, slightly higher than the values indicated in ecoinvent for generic polypropylene and paper packaging (i.e., 32.8 MJ/kg and 14.1 MJ/kg) (Wernet et al., 2016). The ash fraction measured for OPPb and PBp resulted in average values of 12.37 % and 7.67 % of the total mass, respectively. Detected concentrations of metals in the OPPb and PBp samples are reported in Table 2.

4.2. Life Cycle Assessment results

As mentioned in Section 3.1, the results for OPPb and PBp refer to 1000 pieces of packaging material, with the use phase being excluded as considered negligible on the total impact. In Table 3, the environmental impacts of the OPPb and PBp alternatives are compared. The relative difference between the OPPb and PBb alternative referred to each specific scenario is reported in the column classified with "Δ%" columns and indicates a lower impact of PBp in the case the cell is blue-colored or a lower impact of OPPb if the cell is green-colored. Specifically, a first comparison covers only the impacts occurring before the company gate (i.e., *cradle-to-gate* approach), showing a preference for the PBp version for 13 out of 18 midpoint categories, and also for the single score (SS, expressed in millipoints, mPts). The comparison proposed for Scenario 1 (i.e., WtE) and Scenario 2 (i.e., mechanical recycling) showed a lower impact for the PBp option, being this preferable for 10/18 (WtE scenario) and even 16/18 (recycling scenario) midpoint categories, respectively. By including in the model the EoL of materials (second comparison), the SS showed a more evident preference for PBp in both scenarios (higher than 31 %), mainly attributable to the credit for the avoided electricity generation (Scenario 1) and the avoided virgin materials (polypropylene and paper for Scenario 2).

4.2.1. Contribution analysis

In Fig. 2, a graphic comparison between OPPb and PBp is reported for climate change and SS, here selected to enable extensive discussion in the context of previous findings (Delahaye et al., 2023). Fig. 2 also allows us to depict the contribution of each phase in the life cycle. The results for all the environmental categories investigated are reported in Table S7. The CO_2eq emissions occurring before the company gate resulted in being significantly higher for the OPPb, showing a cumulative value of 14.3 kg CO_2eq/FU, against the 8.3 kg CO_2 eq/FU observed for the PBp (−42 %). As already mentioned, in the case of SS, the resulting trends are more comparable, since OPPb overcomes PBp only for 36 mPts (+9 %). Furthermore, the uncertainty associated with the SS results does not allow a clear determination of the more sustainable alternative. This implication is slightly more evident in scenarios where the EoL treatment (especially, recycling) of materials is included in the assessment and is partly due to the use of secondary information for modeling EoL management systems. Greater availability of primary data would allow the use of less severe indicators in the compilation of the Pedigree Data Quality Matrix, improving the accuracy of the obtained results. The semi-finished OPP and paper layers represent, respectively, 56 % and 38 % of the *cradle-to-gate* impacts of climate change. In the case of SS, their contribution is the same (62–63 %). However, the contributions of production and supply of raw OPP and raw paper (excluding the electricity consumed by the OPP and paper semi-finished layers supplier for processing) account for 34 % and 22 % of the potential impact of climate change. The contribution of paper and plastic raw materials on the SS cumulative impact ranges between 36 % (OPPb) and 54 % (PBp). In turn, the PLSSpo is responsible for 44 % and 62 % of the climate change impact, while 38 % and 37 % for SS.

Both for GWP and SS, the sum of the individual contribution rates of transportation, other raw materials, emissions to the atmosphere, and waste management are never higher than 14 %, attesting a secondary role in the total impact. Also, heat consumption presents a relatively low contribution (never higher than 10 % in GWP and SS). PLSSpo electricity, instead, contributes 24 % and 38 % in the case of GWP and 28 % for both OPPb and PBp in SS. By including in the electricity balance also the fraction consumed during the semi-finishing phase at the supplier plant, the whole electricity contribution increases up to 47 % and 53 % for GWP and 55 % and 37 % for SS, highlighting the crucial role of electricity in the overall environmental performance of the system.

For both alternatives and all the environmental categories considered, the impacts associated with EoL are partially or entirely compensated by the credits for avoided products. Concerning OPPb, the recycling scenario performs better than WtE for SS and 9 of 18 categories (including climate change). Thus, results do not identify the better choice among them. On the other hand, in the case of PBp, the WtE result is preferable only for 3/18 (GWP, WCP, and FFP). However, the preferability for these three categories implied a WtE preference also for SS, according to other studies that already highlighted the influence of these two categories on the SS (Arfelli et al., 2024; Bulle et al., 2019).

Regarding the EoL phases, in the case of OPPb, the credits associated with WtE and recycling scenarios provide a significant benefit for both GWP and SS, which results in a net impact reduction. The avoided impacts for the GWP category correspond to about 55 % of the EoL direct impacts, while for the SS the difference between direct and avoided impacts is almost neutral. The trend is reversed in the mechanical recycling scenario since the benefits associated with EoL credits exceed the overall environmental burdens. In the case of PBp, the advantages derived by both the credits of WtE and recycling scenarios are higher than the EoL direct impacts. Computing the credits and direct impacts of the different EoL solutions, we find that for OPPb the preferred choice is mechanical recycling, while for PBp the best overall performance is achieved by opting for WtE. The preferability showed for a WtE scenario for PBp is justified by the high percentage of fossil-based electricity in the PL mix, which confirmed the relevant role of the electricity mix while evaluating the influence of the avoided product in a system (Arfelli et al., 2023). From a wider perspective, packaging has been blamed for representing one of the highest sources of environmental impacts in food production (Licciardello, 2017), even if elsewhere (Kan and Miller, 2022) plastic packaging resulted to be responsible for <10 % of the total life cycle emissions for 23 out of 30 foods examined. By estimating a GWP of a milk chocolate bar at 1210 kg CO_2 eq/FU (Colomb et al., 2015) (FU = 1000 pcs of 100 g), the estimated contribution for packaging would represent the 1.6 % in case of OPPb and the 0.4 % in case of PBp (WtE scenario). Concerning the SS, packaging contributes the 1.0 % and the 0.6 % for OPPb and PBp.

Table 2
Metals concentration in post-use Oriented Polypropylene based packaging (OPPb) and Paper Based packaging (PBp).

	Cr	Zr	V	Al	Ti
OPPb	2.89 ppm	63.56 ppm	2.89 ppm	8948.24 ppm	72.70 ppm
PBp	21.62 ppm	29.20 ppm	16.82 ppm	55,417.60 ppm	3609.16 ppm

Table 3
Comparison of the environmental impacts of Oriented Polypropylene Based packaging (OPPb) and Paper Based packaging (PBp) for the three scenarios (i.e., only direct impacts; Waste-to-Energy, WtE; and Recycling). Values in the Δ% columns indicate a lower impact of PBp (if the cell is blue-colored) and of OPPb (if the cell is green-colored). GWP: Global warming (kg CO_2 eq); ODP, Stratospheric ozone depletion (kg CFC11 eq); IRP, Ionizing radiation (kBq Co-60 eq); HOFP, Ozone formation-human health (kg NOx eq); PMFP, Fine particulate matter formation (kg PM 2.5 eq); EOFP, Ozone formation Terrestrial ecosystems kg NOx eq); TAP, Terrestrial acidification (kg SO_2 eq); FEP, Freshwater eutrophic. (kg P eq); MEP, Marine eutrophic. (kg N eq); TETP, Terrestrial ecotoxicity (kg 1,4-DCB eq); FETP, Freshwater ecotoxicity (kg 1,4-DCB eq); METP, Marine ecotoxicity (kg 1,4-DCB eq); HTPc, Human carcinogenic toxicity (kg 1,4-DCB eq); HTPnc, Human non-carcinogenic toxicity (kg 1,4-DCB eq); LOP, Land use occupation (m^2a crop eq); SOP, Mineral resource scarcity (kg Cu eq); FFP, Fossil resource scarcity (kg oil eq); WCP, Water consumption (m^3).

	To gate			WtE			Recycling		
	OPPb	PBp	Δ%	OPPb	PBp	Δ%	OPPb	PBp	Δ%
GWP	14.30	8.31	-42%	19.10	4.46	-77%	13.90	6.20	-55%
SOD	$5.54*10^{-6}$	$5.43*10^{-6}$	-2%	$2.92*10^{-6}$	$7.13*10^{-6}$	-59%	$5.76*10^{-6}$	$-1.36*10^{-6}$	-124%
IRP	0.42	0.83	-49%	0.33	0.77	-57%	0.41	-5.26	-108%
HOFP	$2.30*10^{-2}$	$2.03*10^{-2}$	-12%	$1.62*10^{-2}$	$1.64*10^{-2}$	-1%	$2.04*10^{-2}$	$1.44*10^{-2}$	-30%
PMFP	$9.65*10^{-3}$	$6.69*10^{-3}$	-31%	$7.49*10^{-3}$	$5.36*10^{-3}$	-29%	$6.22*10^{-3}$	$2.96*10^{-3}$	-53%
EOFP	$2.57*10^{-2}$	$2.31*10^{-2}$	-10%	$1.70*10^{-2}$	$1.80*10^{-2}$	-5%	$2.36*10^{-2}$	$1.71*10^{-2}$	-27%
TAC	$3.05*10^{-2}$	$2.41*10^{-2}$	-21%	$2.38*10^{-2}$	$1.99*10^{-2}$	-17%	$2.68*10^{-2}$	$1.32*10^{-2}$	-51%
FEP	$2.02*10^{-3}$	$5.47*10^{-3}$	-63%	$1.80*10^{-3}$	$5.25*10^{-3}$	-66%	$1.38*10^{-3}$	$3.10*10^{-3}$	-55%
MEP	$3.41*10^{-4}$	$6.76*10^{-4}$	-50%	$2.55*10^{-4}$	$6.88*10^{-4}$	-63%	$3.07*10^{-4}$	$1.11*10^{-4}$	-64%
TETP	2.40	26.50	-91%	18.90	26.60	-29%	2.43	26.30	-91%
FETP	$3.89*10^{-2}$	$1.34*10^{-2}$	-66%	0.60	0.16	-73%	$3.60*10^{-2}$	$2.13*10^{-2}$	-41%
METP	$5.56*10^{-2}$	$3.64*10^{-2}$	-34%	0.62	0.18	-70%	$5.27*10^{-2}$	$4.43*10^{-2}$	-16%
HTPc	$2.74*10^{-2}$	$4.59*10^{-3}$	-83%	$6.20*10^{-2}$	$7.81*10^{-2}$	-21%	$2.71*10^{-2}$	$3.75*10^{-3}$	-86%
HTPnc	0.44	0.28	-35%	7.16	4.87	-32%	0.42	0.25	-41%
LOP	0.25	52.30	-99%	0.18	52.30	-99%	0.18	49.00	-99%
SOP	$2.67*10^{-2}$	$1.03*10^{-2}$	-61%	$2.46*10^{-2}$	$9.42*10^{-3}$	-62%	$2.55*10^{-2}$	$-4.45*10^{-2}$	-274%
FFP	5.60	2.04	-64%	4.00	0.93	-77%	5.60	1.57	-72%
WCP	1.79	0.90	-50%	-0.28	-0.55	-99%	2.40	0.43	-82%
Single score	398.00	362.00	-9%	391.00	245.00	-37%	380.00	262.00	-31%

4.2.2. Sensitivity analysis on the energy mix

Sensitivity analysis was performed to test the robustness of the model created, enabling the identification and quantification of the influence of certain parameters on the environmental impacts of the entire system (Goedkoop et al., 2016). Electricity contributes from an average of 33 % up to 96 % (WCP category) of the total environmental impact. However, the impact of electricity is highly affected by the modeled electricity mix. For this reason, the Polish (PL) energy mix, which was selected as the representative for the case study, was replaced in sensitivity analysis with the European (EU) average energy mix to calculate the resulting changes in the system under scrutiny (Fig. 3). From Fig. 3, it is evident how the reduction of the GWP emissions resulting from the energy mix determines a considerable reduction of the overall GWP. Supposing to shift from the PL mix, which relies 89 % on fossil resources and presents a considerable carbon intensity (0.82 kg CO_2 eq/kWh) (IEA, 2022), to the EU one the OPPb impacts are decreased by 14 %, while the PBp impacts for the 23 % (GWP category). Shifting to the EU mix, the average contribution of electricity remains almost unchanged (33 %), but about 12 categories are positively influenced by reducing the share of fossil sources in the composition mix. The impact category that shows a major worsening is Ionizing Radiation Potential (IRP), because of a larger share of nuclear energy in the EU electricity mix than the PL one (Wernet et al., 2016). The whole set of the obtained environmental impacts is reported in Table S8.

4.2.3. Relevance of waste modelling

As observed in section 4.2.1, the identified EoL scenario could significantly affect the estimation of the environmental impacts. The absence or incompleteness of primary data concerning waste composition and waste treatment inventories is often a main limitation in LCA modeling so average chemical compositions and database processes are typically employed as proxies (Caldeira et al., 2022; Pellengahr et al., 2023). In this study, the former limitation is overcome by using the characterization results for ash composition and metal contents in real waste OPPb and PBp specimens to create an elemental-specific LCA model.

Concerning the environmental impact values estimated for the whole life cycles of OPPbp and PBp, by modifying the EoL inventories, no significant differences for GWP and SS were observed. However, as depicted in Fig. 4, noticeable variations result for some impact categories compared to proxy processes. In particular, for toxicity-related categories (i.e., TETP, FETP, METP, HTPc, HTPnc) impacts are reduced by about 80 % in the OPPb and 40 % in the PBp. In the case of OPPb, the environmental impacts associated with waste composition decreased for 15 midpoint categories. In contrast, ODP, IRP, and WPC results increased. Consequently, SS showed a reduction of nearly 13 %. For PBp, all the examined categories displayed lower impacts and a reduction of 31 % for SS. The whole set of results is reported in Table S9.

4.3. Limits of the study and future perspectives

As mentioned in section 3.2, the manufacturing phase is based on primary information related to real production systems. However, the study presents some limitations summarized as follows: *i)* The raw material supply phase was modeled in consistency with information from the ecoinvent database and not primary data; *ii)* The EoL management was modeled assuming two distinct scenarios (i.e., WtE and recycling). The WtE phase was modeled partly using data from the ecoinvent database and partly through laboratory analyses, which allowed for the calculation of the LHV. Consequently, the potential energy produced in this phase was estimated, and the amount of solid residue and the metals contained in the two packaging formulations was calculated. Regarding material recycling, reference was made to literature data (see section 3.2.4). The choice of mechanical recycling for

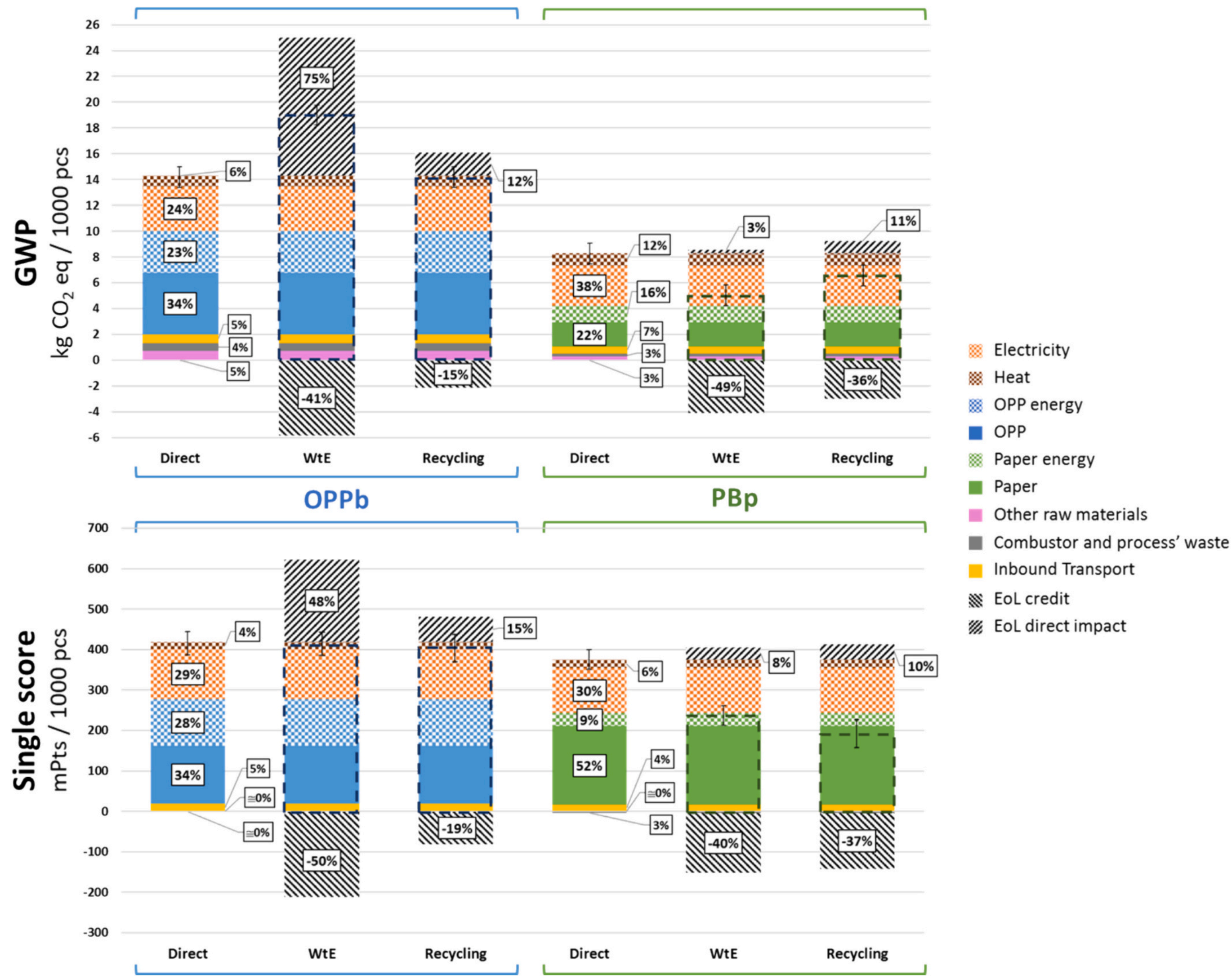

Fig. 2. Life cycle impact evaluation and contribution analysis of the Oriented Polypropylene Based packaging (OPPb) and Paper Based packaging (PBp) products. Scenario 1 (i.e., direct) represents the direct impacts of the system by excluding the End of Life (EoL). Scenarios 2 and 3 (i.e., Waste to Energy, WtE and Recycling) describe the environmental impacts of the system by including the post-use management of the two products. Net environmental impacts in the WtE and Recycling scenarios are represented by dashed lines.

plastic is due to the absence of inventories describing chemical recycling in the literature. All these aspects have been considered in the uncertainty analysis and more severe scores were assigned to secondary data in the pedigree matrix. Once such information becomes available, as well as information related to the operative conditions and emissions of both the WtE and recycling processes, the model can be revised and refined in the future. However, it should be noted that the primary objective of the study is not to focus on recycling processes, but rather to create a complete model, highlighting existing literature gaps, and providing solutions to address the absence of reliable data in the literature with laboratory analyses to obtain material-specific information. In general, the model can be improved for both the cradle-to-gate and gate-to-cradle phases as site-specific information becomes available.

5. Conclusions

In this study, LCA was applied to compare the environmental performance of alternative packaging materials and to evaluate the environmental impacts occurring along the supply chain of OPPb and PBp. The overall results attest that shifting from a plastic-based to a paper-based material could potentially decrease the environmental impacts of packaging for most of the analyzed categories. However, from a life cycle perspective, the relatively low contribution on the total impact of the raw materials for OPP and paper suggests that more effective strategies and policies to reduce the impacts of packaging, especially in terms of climate forcing, should rather focus on the processing phase, especially referring to the electricity mix.

By extending the perspective, it is essential to focus on the electricity contribution to the final impacts. Acting on the electricity mix might be, sometimes, more effective in reducing the total impacts concerning the substitution of raw materials. A relevant reduction (>10 %) was observed for the categories GWP, ODP, TETP, FFP, and LOP (the latter only for OPPb). In other cases (categories: HOFP, EOFP, MET, FETM, HTPc, HTPnc, WCP, and SS), switching from a more carbon-intensive mix (PL) to a less impacting one (EU), does not substantially alter the results, even if auspicial mitigation of the fossil content in the European mix occurring in the next year might bring to further improvements also for the less affected categories. Eventually, a worsening was observed for IRP, PMFP, TAC, FEP, and SOP, due to the increased usage of nuclear energy (especially for IRP).

Concerning EoL management, the substantial difference in calculated environmental impacts between the PWC and EWC raises the

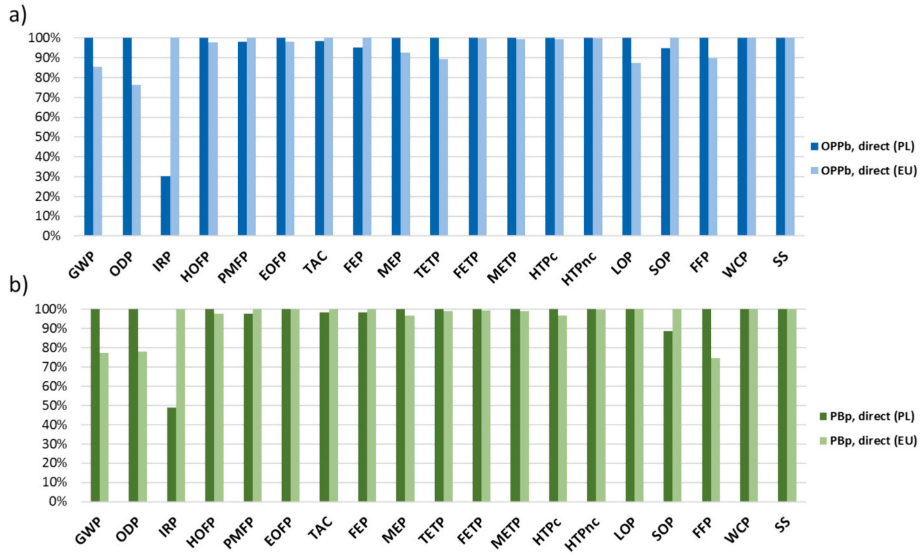

Fig. 3. Sensitivity analysis on Oriented Polypropylene packaging (OPPb) (a) and Paper Based packaging (PBp) (b) based on the energy mix. GWP: Global warming; ODP, Stratospheric ozone depletion; IRP, Ionizing radiation; HOFP, Ozone formation-human health; PMFP, Fine particulate matter formation; EOFP, Ozone formation Terrestrial ecosystems; TAP, Terrestrial acidification; FEP, Freshwater eutrophic.; MEP, Marine eutrophic; TETP, Terrestrial ecotoxicity; FETP, Freshwater ecotoxicity; METP, Marine ecotoxicity; HTPc, Human carcinogenic toxicity; HTPnc, Human non-carcinogenic toxicity; LOP, Land use occupation; SOP, Mineral resource scarcity; FFP, Fossil resource scarcity; WCP, Water consumption; SS, Singe Score.

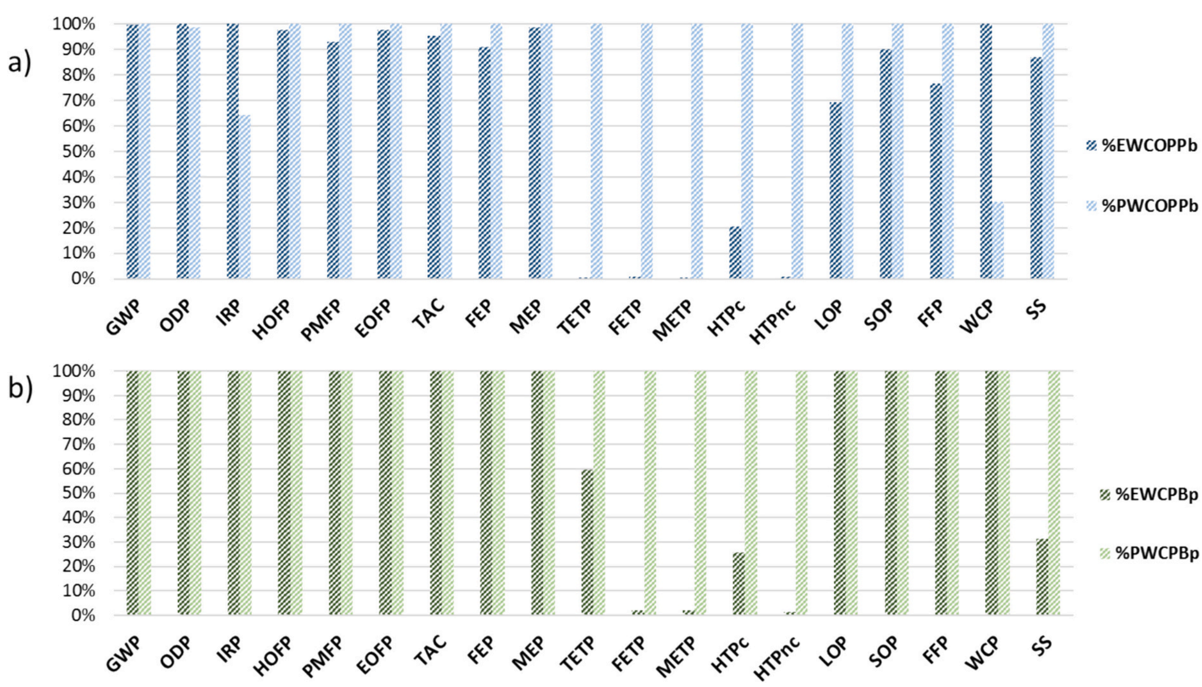

Fig. 4. Comparison between the environmental impacts of EWC (estimated waste composition) and PWC (proxy waste composition) of both OPPb and PBp. GWP: Global warming; ODP, Stratospheric ozone depletion; IRP, Ionizing radiation; HOFP, Ozone formation-human health; PMFP, Fine particulate matter formation; EOFP, Ozone formation Terrestrial ecosystems; TAP, Terrestrial acidification; FEP, Freshwater eutrophic.; MEP, Marine eutrophic; TETP, Terrestrial ecotoxicity; FETP, Freshwater ecotoxicity; METP, Marine ecotoxicity; HTPc, Human carcinogenic toxicity; HTPnc, Human non-carcinogenic toxicity; LOP, Land use occupation; SOP, Mineral resource scarcity; FFP, Fossil resource scarcity; WCP, Water consumption; SS, Singe Score.

possibility of significant variations in the results. While the EoL phase appears to be of marginal importance in the specific case study, the impact of this approach may be more pronounced in different contexts, especially when *cradle-to-gate* impacts are lower or when materials exhibit distinct compositions. Furthermore, the choice to refer to material-specific data may reduce the uncertainty associated with the material's impact value, by reducing the comprehensive uncertainty of the whole examined systems. In the same way, the estimation of the credit associated with the electricity generated in the WtE plant would have been underestimated using secondary data.

Possible follow-ups of this work should prioritize the inclusion of primary data-related waste management scenarios and regionalized impact assessment methods. Especially in the case of the EoL of OPPb, recycling processes other than mechanical (e.g., thermochemical, chemical) could be analyzed and compared to evaluate the potential crediting for avoiding the extraction of virgin material.

LCA is confirmed to be a versatile and reliable tool to characterize the environmental burdens and benefits associated with an industrial system, being supportive of strategic planning and policies that approach the achievement of sustainable production and consumption patterns.

CRediT authorship contribution statement

Francesco Arfelli: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Marlena Roguszewska:** Resources, Data curation, Conceptualization. **Gianluca Torta:** Investigation, Data curation. **Matteo Iurlo:** Resources, Methodology, Investigation. **Daniele Cespi:** Writing – review & editing, Visualization, Validation, Methodology. **Luca Ciacci:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization. **Fabrizio Passarini:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization.

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.spc.2024.06.032.

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