

Comparative life cycle assessment and multi-criteria decision analysis of coffee capsules made with conventional and innovative materials

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ABSTRACT

The following study arises from the need to replace aluminum and polypropylene, from fossil and non-renewable sources, with innovative materials to produce coffee capsules. The analysis was carried out using Life Cycle Assessment (LCA) and Multi Criteria Decision Analysis (MCDA). In the comparison were considered different materials: aluminum capsules, polypropylene, biocompostable plastic in an industrial environment (industrial compost) and biocompostable plastic in a domestic environment (home compost). The results indicate that, for current disposal, biocompostable plastic capsules, particularly those suitable for domestic compost, have lower environmental impacts. These results are also confirmed for the 10-year disposal scenario. Polypropylene capsules demonstrate greater environmental sustainability when considering a recovery rate of 100 % of the raw material. The MCDA analysis confirms that, at the moment, bioplastics represent the solution with the least environmental impact. However, this advantage is reduced if the capsules are made of aluminum and polypropylene using exclusively fully recycled raw material. Furthermore, it appears that the recycling of fossil materials is a viable alternative to bioplastics. It should be noted, however, that polypropylene can be recycled up to three times, unlike aluminum which can be recycled an indefinite number of times.

1. Introduction

The coffee capsule market has experienced significant growth in recent years, as their consumption is stimulated by their simplicity and speed of use. Moreover, the capsules highlight advantages compared to the corresponding cellulosic pods, since they are more impermeable to humidity and oxygen, ensuring better preservation of the coffee (Martin and Schouten, 2014; Cincotta et al., 2020). Coffee capsules are mostly made of aluminum and polypropylene (Gökelma et al., 2020; Domingues et al., 2020). In all, over 1.5 billion coffee capsules are sold in the world every year (Angelino et al., 2018). All these pods generate tons of waste, which only worsens the discomfort of environmental pollution. Aluminum is a lightweight material that is commonly used for the production of packaging, for example as an alternative to common plastic bottles (Tamburini et al., 2021) or for the production of soft drink cans (Niero and Olsen, 2016). One of the main environmental problems is the extraction of bauxite, a naturally occurring heterogeneous compound composed of aluminum hydroxides (Ma et al., 2022). Bauxite extraction has a high impact on the entire life cycle of aluminum production as highlighted in Farjana et al. (2019), especially in the

categories related to the use of fossil resources. In the same study, it is stressed that the alumina production process has a significant impact due to the extraction of natural gas and the use of fuel oil. In contrast, the impacts of aluminum smelting are mainly related to electricity consumption. Polypropylene is a thermoplastic material that guarantees high heat distortion temperature, transparency, flame resistance and dimensional stability (Spoerk et al., 2020). It is commonly used for the production of packaging, crates and automotive spare parts (Mannheim and Simenfalvi, 2020). Most of the impacts in the life cycle of polypropylene packaging are attributable to the material production process, since it requires the extraction of oil and natural gas, which are essential to obtain the necessary raw material (Yadav et al., 2024). The production processes of the semi-finished or finished product, such as extrusion or forming, have lower impacts than the production of the polymer as analyzed in Maga et al. (2019).

Aluminum and polypropylene are intrinsically associated with significant environmental impacts, as highlighted by Paraskevass et al. (2015), underlining the urgent need to identify more sustainable alternatives. This need is further amplified by rigorous European regulations, which, by promoting the transition from a linear to a circular model

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(Bucknall, 2020), aim to reduce both the quantity of waste generated and the exploitation of virgin resources. For aluminum and plastic capsules, another problem is linked to the recycling process (Marinello et al., 2021), as the separation between packaging and coffee turns out to be a complex and expensive operation, therefore very often the capsules are disposed of to landfill or waste-to-energy plant. This research aims to conduct a more detailed analysis on the life cycle of the capsule, focusing on the material used for its manufacture and its purpose, excluding the stage of production of coffee.

The objective of the present study is, therefore, to carry out a comparative evaluation using LCA methodology between coffee capsules made with four different materials, two of fossil origin, aluminum and polypropylene, and two composites which consist of two bioderived polymers and talc with different share in mass and can be composted in either home or industrial conditions. The study was carried out by investigating the entire life cycle of the capsule, also considering the role on it of secondary packaging. The analysis conducted is of the cradle-to-cradle type and therefore investigates the entire life cycle of the coffee capsules, in such a way as to consider the reuse of resources, as it would be typical of a circular economy approach. The study also evaluates the possibility of replacing virgin aluminum and polypropylene for the manufacturing of the capsules, with equivalents in secondary raw materials, coming from the recycling chain. This aspect is of primary importance as the Italian recycling chain and, more generally, the European one is much more advanced than the composting one. On the other hand, several materials from fossil sources can be recycled an infinite number of times, representing an enormous resource for multiple transformation processes or a waste if their potential is not fully exploited. In addition to the LCA analysis, the present study also proposes a multivariate analysis, namely Multi Criteria Decision Analysis (MCDA) based on the results of the LCA analysis, as well as the introduction of two further indicators relating to the rate of reuse and recycling of the materials taken into consideration. These indicators are, namely, the Material Reutilization Score (MRS) and the Material Circularity Indicator (MCI). They can be both used as valuable predictors for carrying out circularity assessments of a good/service (Niero and Kalbar, 2019). The MCDA has, therefore, been planned to allow an integrated approach to the problem of managing the end of life of coffee capsules, in such a way as to identify the most circular alternative among the technological solutions that involve raw materials from fossil source (i.e., aluminum and polypropylene) or those relying on raw materials coming from renewable sources (i.e., bioplastic materials that are compostable in industrial and domestic environments).

2. Literature review

LCA, acronym for Life Cycle Assessment, allows the evaluation of the environmental impacts linked to a process or product, also considering different disposal scenarios (Desole et al., 2023). In the current scientific landscape, studies relating to the environmental impacts of coffee capsules are rather limited. Tonelli et al. (2019) analyzed coffee capsules made of three different materials using LCA analysis: aluminum, polypropylene and compostable biopolymer, i.e. polylactic acid (PLA). Polypropylene proved to be the material with the most significant impact in all categories analyzed such as acidification, eutrophication, global warming, photochemical oxidation, ozone depletion and abiotic depletion, followed by bioderived polymer and aluminum. The biopolymer proved preferable when the production of biogas, rather than compost, was derived from organic waste. In Soares et al. (2022) a comparative analysis is carried out between the conventional methods of recycling coffee capsules and the production process of composite material partially reinforced with bagasse fiber, coming from the cultivation of sugar cane, which can be, subsequently, reused for the capsule production. In the latter case, a lower environmental footprint in terms of global warming and eutrophication compared to the capsule recycling process was found. In contrast, capsule recycling proves to be more

sustainable in terms of terrestrial ecotoxicity and non-carcinogenic toxicity to humans. There is no study in the literature in which a comparison of the environmental footprint of capsules is made focusing on capsules manufactured with recycled materials, such as aluminum and polypropylene. Recycled aluminum and polypropylene are already widely exploited as secondary raw materials in the construction sector (Hendriks and Janssen, 2003; Bolden, 2013). The recourse to recycled materials could allow the drastic reduction of the damage to the environment and human health caused using capsules. Products manufactured from recycled materials are, in fact, extending their presence on the market, as consumers show a positive attitude, associating them with minimal environmental impacts (Polyportis et al., 2022; Kuah and Wang, 2020). In addition, the possibility of making the capsules using bioplastics with a lower environmental footprint than polylactic acid (PLA), such as bioplastics based on polyhydroxyalkanoates (PHAs) which, unlike PLA, are compostable in home environment (Z. Naser et al., 2021) has never yet been considered, too. Bioplastics compostable in the home environment are low-impact materials compared to fossil-resource plastics (Rosenboom et al., 2022). Compared to industrial composting, in fact, disposal in a domestic composter allows avoiding the collection of urban waste, as well as providing better control over the treated materials (Colón et al., 2010). In domestic composting, biodegradation does not take place under strictly controlled conditions, in terms of temperature and humidity (Rujnić Havstad et al., 2021). Through domestic composting, it is therefore possible to obtain high quality and stable compost as reported by Cafiero et al. (2021). This quality is strongly influenced by the levels of humidity and temperature reached, respectively above 50 % and 25, with biodegradation percentages obtained exceeding 90 %, both in electromechanical and static domestic compost heaps. Industrial composting is currently more widespread than domestic composting because of the large volumes of material it can handle. However, it requires waste collection and transport to the composting site, as well as the adoption of infrastructure (Quecholac-Piña et al., 2017). It is not always possible to achieve optimal conditions in terms of compost and process management, because of the production of microplastics and the use of chemical compounds to completely degrade bioplastics, which have a high environmental burden (Ahsan et al., 2023).

3. Methods

3.1. Materials

Aluminum is a light metal with good mechanical resistance (Zhuang et al., 2023), with density and melting temperature of 2.7 kg/dm³ and 660 °C, respectively (Glam et al., 2014). Its characteristics are well suited to being used in the packaging sector. In addition to its low weight, aluminum guarantees good gas impermeability properties. Polypropylene is a thermoplastic polymer derived from fossil sources, characterized by low processing costs and good stiffness compared to other types of thermoplastic materials (Maddah, 2016; He et al., 2003). The two biopolymeric materials considered in this study have polybutylene succinate (PBS), polybutylene adipate-co-terephthalate (PBAT), poly-3-hydroxybutyrate-co-3-hydroxyhexanoate (P(3HB)(3HH)) as main polymeric phases. Talc is added to each formulation as mineral filler. The compositions of the two compostable materials (industrial and home compost, respectively) are shown in Table 1.

PBS is a class of aliphatic polyester, obtained from succinic acid and 1,4-butanediol, characterized by excellent thermal resistance (Barletta et al., 2022). PBAT is a biodegradable aliphatic-aromatic copolyester of petroleum origin (Lee et al., 2022), based on the monomers 1,4-butanediol, adipic acid and terephthalic acid. It has properties similar to those of low density polyethylene, thanks to its molecular structure and low molecular weight (Mohanty and Nayak, 2012). It also boasts high biodegradability, as well as good mechanical resistance and flexibility, which makes it suitable for the production of food packaging (Thiyaku,

Table 1
Formulations of industrial-compost and home-compost biopolymers.

Element	Industrial compost (weight%)	Home compost (weight%)
Polybutylene succinate	69.6 %	16 %
Polybutylene adipate-co-terephthalate	16.2 %	
Poly-3-hydroxybutyrate-co-3-hydroxyhexanoate		64 %
Talc	10 %	18.30 %

2022; Muthuraj et al., 2018). P(3HB)(3HH) is a biodegradable and compostable biopolymer of the polyhydroxyalkanoate (PHA) family, which has good mechanical properties and is particularly suitable for being processed by extrusion processes (Eraslan et al., 2022). This biopolymer is also often used for the production of food packaging, flexible films, disposable plastic bags (Ivorra-Martinez et al., 2020). Talc is a mineral filler that is often added in the biopolymeric formulation as it improves water vapor and oxygen barrier properties, increases thermal and dimensional stability and reduces the cost of the material. Both for polypropylene capsules and for those made of bioplastic material, the production of a triple casing composed of aluminum, polypropylene and polyester is envisaged. In the case of aluminum capsules, corrugated cardboard packaging is sufficient as secondary packaging, as aluminum itself has sufficient oxygen barrier properties.

3.2. Software and standards, objective, functional unit and field of application

The software used for the analysis is SimaPro version 9.3 (Prè Consultants 2021). It provides six different databases, which contain the inventory data of a vast range of industrial processes. Based on the ISO 14040 and ISO 14044 regulations (Finkbeiner et al., 2006), the LCA methodology involves the following four steps: 1) Definition of the objective and field of application; 2) Inventory analysis; 3) Impact assessment; 4) Interpretation.

The objective of the LCA analysis is to evaluate the environmental impact of the capsule containing coffee made with four different materials: aluminum, polypropylene, home compost bioplastic, industrial compost bioplastic. The functional unit refers to a capsule containing 5 g of coffee, with the following dimensions:

1. Base diameter: 36.8 ± 0.1 mm,
2. Height: 28.0 ± 0.2 mm,
3. Base thickness: 1.4 ± 0.1 mm,
4. Diameter of the junction point between base and capsule body: 30.0 ± 0.1 mm.

Fig. 1a and b show the technical drawing and an image of the capsule, taken from the study of Barletta and Gisario (2021), as well as the dimensions of the capsule.

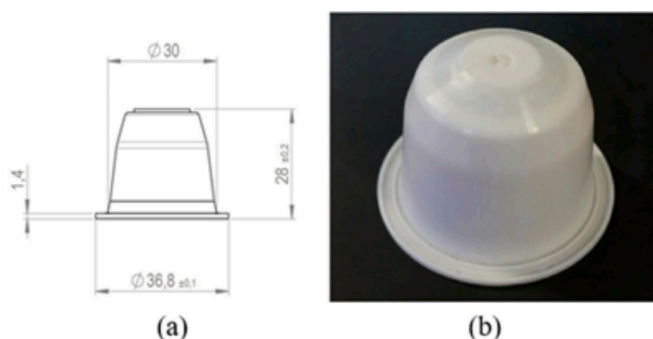


Fig. 1. (a) Technical drawing of the capsule, (b) Image of the capsule.

The weight of the aluminum capsule amounts to 0.95 g, lower than that of the plastic and bioplastic counterparts, due to the lower density of the aluminum itself. For the polypropylene capsule, home compost bioplastic and industrial compost bioplastic the weight of the capsule amounts in all cases to 2.7 g. The weight of the secondary packaging, both for cardboard and for the multilayer, is estimated based on that of the functional unit, equal to 5 and 2 g respectively, that is, the quantity necessary to contain a capsule.

3.3. System boundaries

Figs. 2, 3, 4 and 5 show the boundaries of the system. The analysis carried out is of the cradle-to-cradle type. It aims at evaluating the entire life cycle of the coffee capsule, considering at the end of its life the possibility of it being reused for the same purposes or with different purposes (respectively as in the case of recycling and composting) (Desole et al., 2022). The company that produces aluminum is located in France, a country where bauxite extraction also takes place. The company that deals with aluminum drawing, capsule filling, packaging and distribution is located in northern Italy. For polypropylene, the oil extraction takes place in Asia, while the granules (i.e., the plastic compounds) are produced in a company located in northern Italy. Both extrusion and molding are carried out in the capsule manufacturing company. Since it is the same type of product, the pre-distribution processes are the same for all capsules, both for decontamination and to produce secondary packaging. Life cycle analysis excluded coffee production and capsule use, such as infrastructure construction, while secondary packaging production is included in the analysis. As regards end-of-life management, in the case of aluminum and polypropylene capsules, landfill disposal, incineration with energy recovery and recycling processes were considered, while for both domestic and industrial compost bioplastics the composting process is considered. For the secondary packaging of aluminum, plastic and bioplastic capsules, the same processes of landfill, incineration and recycling of primary packaging are considered. The talc production process was not included in the flow chart, as it is considered to be purchased externally.

3.4. Inventory analysis

The analysis was conducted considering both primary and secondary data, focusing in particular on modelling the production processes of aluminum, polypropylene and bioplastics. For the production of primary aluminum, the “Aluminum, primary, ingot (RoW) production” process is taken from the Ecoinvent 3.8 database. Among the process inputs, to produce 0.95 g of primary aluminum, natural gas was considered as a fuel to heat the molten aluminum to 750 °C, for an amount of 0.1 MJ. Furthermore, alloy elements such as magnesium, silicon and manganese are included in a percentage of 10 % of the total weight. The production of primary aluminum involves the use of argon and nitrogen with a weight of 1.5×10^{-5} kg and 6×10^{-6} kg respectively. The emissions from the aluminum production process are reported in the Supplementary Information. In the aluminum drawing process, an electrical energy consumption of 1.5 Wh is necessary, while the use of lubricants is essential (Chen et al., 2023). The decontamination phase, on the other hand, requires the use of steam to eliminate any impurities. As regards the aluminum capsules, their transport from the primary aluminum producing company, located in France, was taken into account. This transport is carried out using a fully loaded 32 ton truck, over a distance of 1650 km. The company, which deals with both the drawing of aluminum and the filling of capsules with coffee and further packaging for distribution, is located in northern Italy. The production of polypropylene granules was modeled based on the process from the Ecoinvent 3.8 database “Production of polypropylene, granulate (RER)”. In this process, a water consumption of 2×10^{-3} m³ is estimated, while the electricity and heat consumption values amount to 0.35 Wh and 0.05 MJ, respectively. In the case of home composting bioplastics, the

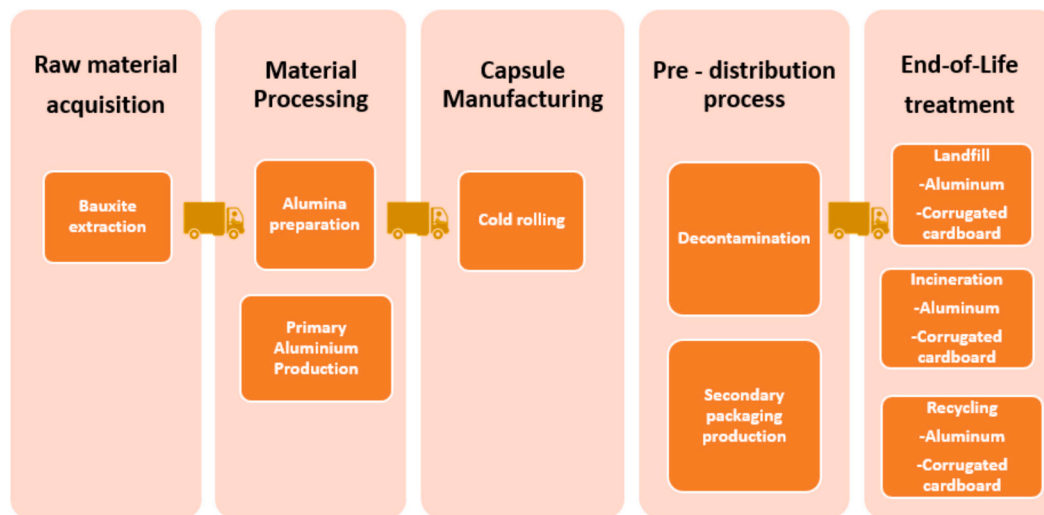


Fig. 2. Boundaries of the aluminum capsule system.

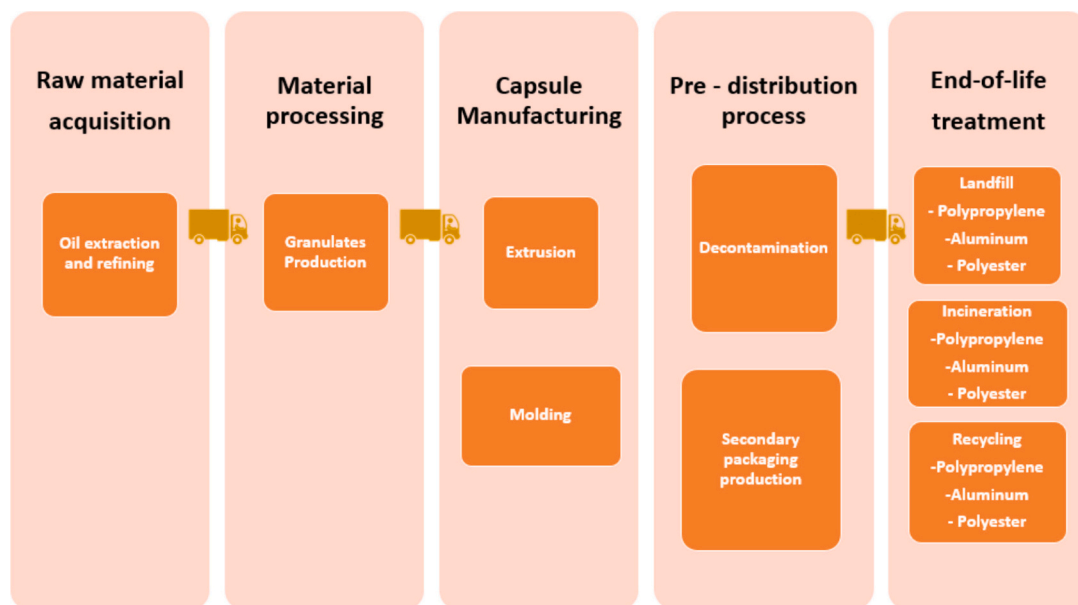


Fig. 3. Boundaries of the polypropylene capsule system.

production of PBAT granules was modeled based on data provided by Saibuatrong et al. (2017), as there are no specific processes in the SimaPro database. The production of 3 g of PBAT involves 1.23 g of 1,4-butanediol (BDO), 1.11 g of adipic acid (APA) and 0.99 g of terephthalate acid (TPA), with a synthesis efficiency of 90 % (Choi et al., 2018). The production of BDO involves the production of bioethanol and succinic acid. Molasses for bioethanol production requires 1.52 g of sugar cane, 0.76 g of water and 0.01 g of calcium hydroxide. The production of PBS is modeled as carried out in Cheroennet et al. (2017), which includes the synthesis of 1,4-butanediol and succinic acid used for the former, the same inputs defined for PBAT. Table 2 shows the inputs for the production of 1,4-butanediol (BDO), adipic acid (APA), terephthalate acid (TPA), bioethanol and succinic acid. The data relating to the production process of P(3HB)(3HH) granules were extracted from the Ecoinvent 3.8 software database, considering a production process based on agricultural waste from the cultivation of corn. The extrusion of the P(3HB)(3HH) granules was modeled considering the electrical energy consumption equal to 0.66 Wh. The molding of polymeric materials was modeled based on the operational settings contained in the

Ecoinvent 3.8 database, considering a consumption of water and electricity of 0.005 m³ and 1.69 Wh, respectively. For the distribution of the finished product, average distances of 300, 600 and 800 km have been established, corresponding to the destination areas in northern, central and southern Italy, respectively. Delivery is carried out using 32-ton trucks. The study's Life Cycle Inventory has been included in the Supplementary Information section.

Background data in this study concern the emissions and energy consumption associated with various processes. On the contrary, the foreground data concentrate on the production stages of the semi-finished product and the finished product, as well as on the disposal and creation of secondary packaging. The system model considered is the Allocation at Point of Substitution (APOS), included in the Ecoinvent 3.8 database.

3.5. Data quality analysis

Accurately assessing data quality is critical to conducting a comprehensive life cycle analysis. Widely used methods include the

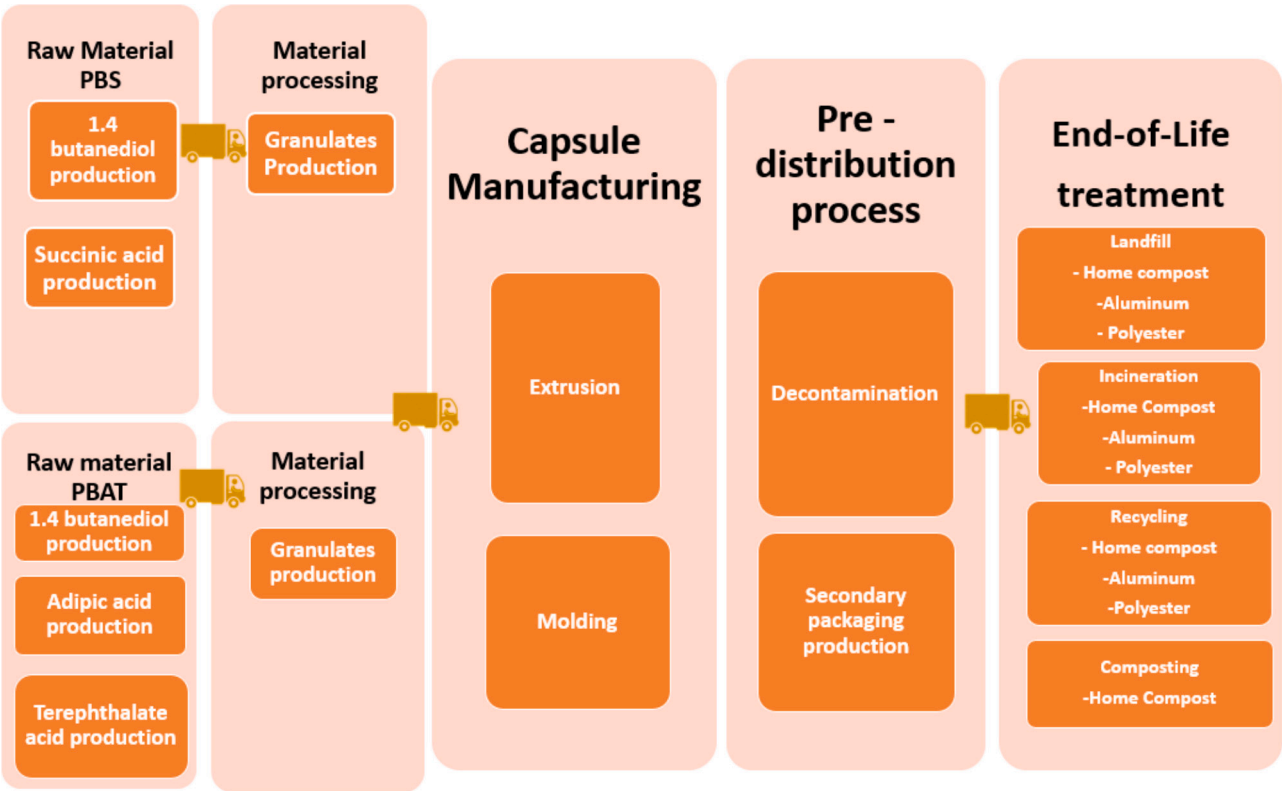


Fig. 4. Boundaries of the Industrial Compost with Polybutylene succinate (PBS) and Polybutylene adipate-co-terephthalate (PBAT) bioplastic capsule system.

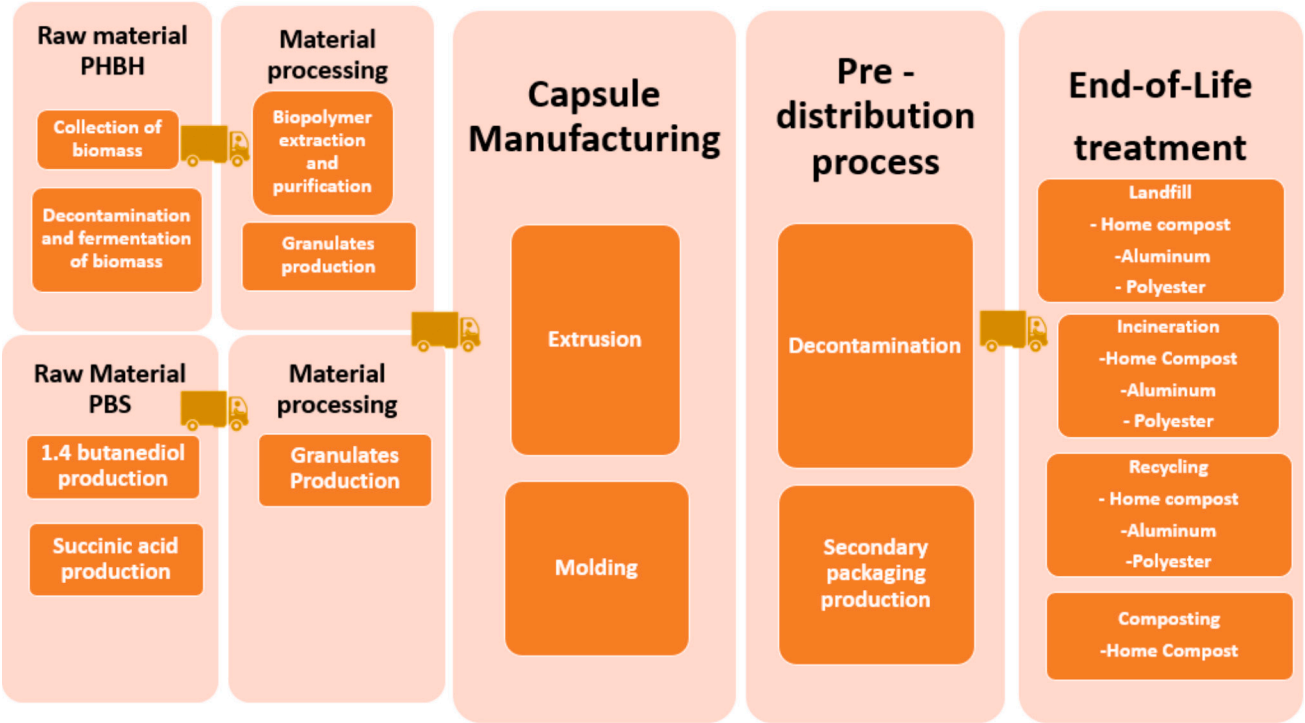


Fig. 5. Boundaries of the Home-compost bioplastic with Poly-3-hydroxybutyrate-co-3-hydroxyhexanoate (PHBH) and Polybutylene succinate (PBS) capsule system.

ILCD method (European Commission, 2010), in accordance with ISO 14040 and 14,044. To carry out this analysis it is necessary to define the Pedigree matrix (Chen and Lee, 2021), that analyzes 6 quality parameters: Technological representativeness (TeR), Geographical representativeness (GR), Temporal representativeness (TiR), Completeness (C),

Parameter uncertainty (P) and Methodological appropriateness and consistency (M). In Table 3 the Pedigree matrix is shown (Füchsl et al., 2022).

The Parameter uncertainty (P) is the accuracy of inventory data, particularly those relating to direct measurements. For each require-

Table 2

Input of the production of 1,4-butanediol (BDO), adipic acid (APA), terephthalate acid (TPA), bioethanol and succinic acid.

BDO INPUTS	BIOETHANOL	3×10^{-3} g
	SUCCINIC ACID	1.3 g
	ELECTRICITY	3×10^{-4} Wh
	NATURAL GAS	6×10^{-4} J
APA INPUTS	NITRIC ACID	0.43 g
	CYCLOHEXANE	0.75 g
	WASTE WATER	10 g
	ELECTRICITY	1.06 Wh
TPA INPUTS	HEAT	31.3 J
	PARAXYLENE	0.66 g
	WASTE WATER	0.21×10^{-3} m ³
BIOETHANOL INPUTS	ELECTRICITY	0.45 Wh
	MOLASSES	3.49 g
	WASTE WATER	13.46 g
	ELECTRICITY	0.24 Wh
SUCCINIC ACID INPUTS	STEAM	4.49 g
	DEXTROSE	2.70 g
	SODIUM CHLORIDE	0.18 g
	CARBON DIOXIDE	0.54 g

ment, a value between 1 and 5 is assigned, where 1 is the highest quality level and 5 the lowest. Eq. (1) shows the formula Data Quality Rating (DQR), which allows calculating the average of the indicators and the overall level of data quality.

$$DQR = \frac{TeR + GR + TiR + C + P + M + X_w * 4}{i + 4} \quad (1)$$

where X_w represents the lowest quality level obtained, indicated by the highest numerical value among the data quality indicators, and i indicates the number of applicable data indicators. Table 4 presents the correspondences concerning the quality level of the data obtained (Godoy León and Dewulf, 2020). For values between 1.0 and 1.6, the data quality is very high, while for values between 1.7 and 2.4 the data quality is high. If DQR is >2.5 the data quality is satisfactory, while for values above 3.3 the quality is low. For aluminum and polypropylene capsules, the evaluation data are taken from the Ecoinvent 3.8 database, while for industrial variants and home compost, the data come from literary sources as indicated in Section 3.4. As regards the production of

P(3HB)(3HH) granules, data are extracted from Ecoinvent 3.8.

3.6. Circular footprint formula

The Circular Footprint Formula (CFF) has been defined by the European Commission for the Product Environment Footprint (PEF) guide, with the aim of evaluating all possible scenarios and managing the multifunctionality of the end of life (Malabi Eberhardt et al., 2020). These scenarios include recycling, reuse, landfill and incineration with or without energy recovery, for both closed and open loop systems (Zampori and Rana, 2019). The CFF allows the modelling of product waste, through a combination of material, energy and disposal (Scrucca et al., 2021). This encompasses the production impacts, the burdens and advantages stemming from the use of secondary materials in both input and output phases, as well as energy recuperation and waste disposal. In Eqs. (2), (3) and (4) the formula for CFF is shown, in terms of material, energy and disposal.

$$\text{Material} : (1 - R_1)E_V + R_1x \left(AE_{recycled} + (1 - A)E_V x \frac{Q_{Sin}}{Q_P} \right) + (1 - A)R_2x \left(E_{recyclingEoL} - E_V^* x \frac{Q_{Sout}}{Q_P} \right) \quad (2)$$

$$\text{Energy} : (1 - B)R_3x (E_{ER} - LVHxX_{ER,heat}xE_{SE,heat} - LVHxX_{ER,elec}xE_{SE,elec}) \quad (3)$$

$$\text{Disposal} : (1 - R_2 - R_3) x E_D \quad (4)$$

Table 5 explains the terms in Eqs. (2), (3) and (4).

A , B , R_1 , R_2 and R_3 are dimensionless, instead $E_{recycled}$, $E_{recyclingEoL}$, $E_{SE,heat}$ and $E_{SE,elec}$ are thus vectors.

Table 4

Data quality indicator and level.

Data quality indicator	Data quality level
1.0–1.6	Very high quality
1.7–2.4	High quality
2.5–3.2	Satisfactory quality
3.3–4.0	Low quality

Table 3

Pedigree matrix.

Indicator score	Explanation	1	2	3	4	5
TeR	The degree of deviation of inventory data from the technology actually used	Data from enterprises, processes and materials under study	Data from processes and materials under study (i. e. identical technology) but from different enterprises	Data from processes and materials under study from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology
GR	To what extent the data effectively reflect the real geographical situation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
TiR	That is the age and the level of updating of the data	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference of the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or >15 years of difference to the time period of the dataset
C	That is the percentage of resource flows and emissions considered during the inventory phase	Representative data from all sited relevant for the market considered, over an adequate period even out normal fluctuation	Representative data from >50 % of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sited (<50 %) relevant for the market considered or >50 % of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
M	Compliance with the methodological requirements established by the reference standards	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate

Table 5

Term of the circular footprint formula.

A	Allocation factor for sharing burdens and credits between supplier and user of recycled materials
B	Allocation factor of energy recovery processes. It applies both to burdens and credits
Q_{Sin}	Quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution
Q_{Sout}	Quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution
Q_P	Quality of the primary material, i.e. quality of the virgin material
R_1	The proportion of material in the input to the production that has been recycled from a previous system
R_2	The proportion of the material in the product that will be recycled (or reused) in a subsequent system.
R_3	The proportion of the material in the product that is used for energy recovery at EoL
$E_{recycled}$	Specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process
$E_{recyclingEoL}$	Specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including the collection, sorting and transportation processes
E_V	Specific emissions and resources consumed (per functional unit) arising from the acquisition and preprocessing of virgin material
E_V^*	Specific emissions and resources consumed (per functional unit) arising from the acquisition and preprocessing of virgin material assumed to be substituted by recyclable materials
E_{ER}	Specific emissions and resources consumed (per functional unit) arising from the energy recovery process
$E_{SE\ heat}$ and $E_{SE\ elec}$	Specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively
E_D	Specific emissions and resources consumed (per functional unit) arising from the disposal of waste material at the analyzed product's EoL, without energy recovery
$X_{ER\ heat}$ and $X_{ER\ elec}$	The efficiency of the energy recovery process for both heat and electricity
LVH	Lower heating value of the material in the product used for energy recovery

3.7. End of life scenario

In this LCA study, two material disposal scenarios are examined: one that represents the current disposal scenario and the other simulating the potential situation in Italy in 2033 (i.e., in ten years). Current and future disposal rates are shown in Table 6 and concern mechanical recycling and incineration with energy recovery. The type of landfill concerned is non-hazardous waste. For aluminum, data updated to 2022 from the National Aluminum Packaging Consortium indicate a recycling rate of 67 %, higher than the 45 % of polypropylene, compliant with European Union Directive 904/2019. Moreover, the data of the disposal of the polypropylene and the bioplastic are defined through Italian Consortia like Higher Institute for environmental protection and research (ISPRA) and the National Consortium for the organic recycling of biodegradable and compostable plastic packaging (Biorepack).

In the future disposal scenario, an increase in the percentage of landfill and composting is expected for biopolymers (to 31 % and 61 %, respectively) and an increase in recycling for aluminum (77 %) and polypropylene (57 %) is expected, too. For bioplastics, despite their technical recyclability, recycling is limited as they do not fully meet the standards of biological plastics, making them less competitive than their petrochemical counterparts. For incineration a percentage of heat recovery of 75 % was considered (Cucchiella et al., 2014), as well as the efficiency of the mechanical recycling process (Bernat, 2023).

For secondary corrugated cardboard packaging, disposal is based on the ISPRA percentages, as reported by Desole et al. (2024). In the case of the triple-layer packaging made of aluminum, polyester, and polypropylene, the disposal scenario aligns with that already considered for aluminum and fossil plastic in the primary packaging.

A third and final scenario was also considered. In this scenario, the

Table 6

Current and Future disposal scenario.

Current disposal scenario		
Aluminum	Landfill	28 %
	Incineration	5 %
	Mechanical recycling	67 %
Polypropylene	Landfill	14 %
	Incineration	41 %
	Mechanical recycling	45 %
Home Compost biopolymer	Landfill	36 %
	Incineration	8 %
	Mechanical recycling	10 %
Industrial Compost biopolymer	Composting	46 %
	Landfill	36 %
	Incineration	8 %
	Mechanical recycling	10 %
	Composting	46 %
Future disposal scenario		
Aluminum	Landfill	20 %
	Incineration	3 %
	Mechanical recycling	77 %
Polypropylene	Landfill	10 %
	Incineration	33 %
	Mechanical recycling	57 %
Home Compost biopolymer	Landfill	31 %
	Incineration	2 %
	Mechanical recycling	6 %
Industrial Compost biopolymer	Composting	61 %
	Landfill	31 %
	Incineration	2 %
	Mechanical recycling	6 %
	Composting	61 %

two fossil materials, aluminum and polypropylene, made from 100 % recycled raw materials, were also taken into account, while maintaining the average disposal percentages shown in Table 6. In assessing the future scenario, changes in the background system, such as alterations in the electricity production mix, are explicitly excluded from consideration. In managing the complexity of multifunctionality, the ‘substitution’ approach is adopted to eliminate extra functions and subtract the avoided burdens. This approach is evident above all in the modelling of the end of life (EoL), where both incineration and recycling have avoided products, such as recovered heat and plastic granulate. In this way, the multi-product system converts into a single product system. The modelling of biogenic carbon and absorption was conducted by reference to the work of Hoxha et al. (2020), and using the 0/0 approach, commonly known as the neutral carbon approach. This method assumes that CO₂ emissions by a product of biological origin during its life cycle are offset by equivalent CO₂ absorption during biomass growth. Therefore, biogenic carbon dioxide emissions were not considered in the calculation. About biogenic methane in composting, it has been taken into account both in the domestic and industrial composting process, evaluating emissions according to the quantities defined by the Ecoinvent 3.8 database.

3.8. Evaluation method and impact categories

The analysis method used is IMPACT World+, a global environmental methodology designed to quantify impacts on human health and ecosystems. This method represents an advancement compared to previous methodologies such as IMPACT 2002+, LUCAS and EDIP (Joliet et al., 2014; Toffoletto et al., 2007). By means of the use of IMPACT World+, it is possible to conduct an evaluation on different aspects, with three main points of view: (1) impact categories, (2) damage categories, (3) normalization. In the specific case of this analysis, 21 impact categories were taken into consideration, excluding long-term ones that cover a time period exceeding 100 years. The impact categories considered are: (i) Climate change, human health (CC-HH), (ii)

Photochemical oxidant formation (POF), (iii) Ionizing radiation, human health (IR-HH), (iv) Layer of ozone depletion (OLD), (v) human cancer toxicity (HT-C), (vi) human non-cancer toxicity (HT-NC), (vii) particulate matter formation (PMF), (viii) water availability, human health (WA-HH), (ix) Climate change, ecosystem quality (CC-EQ), (x) Marine acidification (MA), (xi) Freshwater ecotoxicity (FE), (xii) Marine acidification fresh water (FA), (xiii) Terrestrial acidification (TA), (xiv) fresh water eutrophication (FEU), (xv) marine eutrophication (ME), (xvi) ionizing radiation, ecosystem quality (IR-EQ), (xvii) land transformation (LT), (xviii) land occupation (LO), (xix) Water availability, freshwater ecosystem (WA-FE), (xx) Water availability, terrestrial ecosystem (WA-TE), (xxi) Thermally Polluted Water (TPW). The two reference damage categories are mainly Ecosystem Quality (EQ) and Human Health (HH). The IMPACT World+ method also includes a damage normalization phase, using the factors illustrated in Table 7.

LCA categories have been chosen with the aim of understanding climate change, ozone depletion, eutrophication and acidification, focusing on both an intermediate analysis as a hotspot and endpoint, on the quality of the ecosystem and human health. The method used, IMPACT World +, is widely recognized globally and is commonly used in the field of analysis with the borders of the Italian system (Canaj et al., 2021). As regards damage categories, the resource category does not constitute a critical point of the system.

Impact World+ is a multi-impact method that differs from the Recipe in that it allows you to assess the short and long-term impacts, considering time intervals over 100 years. As indicated by Hernández-Padilla et al. (2017) during the characterization phase, characterization factors are accessible on a global, continental and regional scale.

3.9. Economic circularity indices and multi-criteria decision analysis

3.9.1. Economic circularity indices

The circular economy promotes the “restorative use” of resources, reintegrating discarded materials into the system rather than considering them waste (Geisendorf and Pietrulla, 2018). This contrasts with the prevailing linear model, which has caused environmental damage (Korhonen et al., 2018). The circular approach emphasizes reuse, regeneration, renewal and repair, following the principles of the 4Rs: reduce, reuse, recycle and recover (Kirchherr et al., 2017). The circularity indices analyzed are the Material Circularity Indicator (MCI) and the Material Reutilization Score (MRS). The MCI, on a scale of 0 to 1, measures the circularity of product, with 0 indicating a linear pattern and 1 a full circular pattern. In this analysis, the tool available on the Ellen MacArthur Foundation website was used: <https://ellenmacarthurfoundation.org/material-circularity-indicator>.

The formula for calculating the Material Circularity Indicator was adopted by the study Desole et al. (2024).

The MRS is the index that expresses the quantity of reused material considering the two variables, the intrinsic recyclability of the product (IR), i.e., the percentage of material that can be recycled at least once after use and the recycled content (RC), i.e., the percentage of recycled material within the product. The MRS can take a value between 0 and 100 and can be expressed as in Eq. (5):

$$MRS = \{[(\%IR \text{ of product} * 2)] + [(\%RC \text{ in product} * 1)]\} / 3 \quad (5)$$

The Material Reutilization Score represents a weighted average of the two variables considered, the first being given double the weight of the second.

Table 7

Units of measurement and normalization factors for damage categories.

Damage categories	Unit	Normalization factors
Human health	DALY	13.7
Ecosystem quality	PDF.m ² .year	0.000101

3.9.2. Multi-criteria decision analysis

Once the indices have been defined, it is possible to carry out an MCDA, which allows you to combine the MCI and the MRS with the LCA indicators, which refer to the two damage categories HH and EQ.

It is proposed to combine two indices, MRS and MCI, to conduct a comprehensive assessment of the environmental sustainability of the system. This implies the association of indicators that address complementary aspects, such as the circularity of materials (MCI) and their reuse (MRS). In addition, these indicators are also intended to be used in business contexts, as defined by Linder et al. (2017).

To carry out such a type of analysis, it was decided to apply the TOPSIS method (Technique for Order by Likely to Ideal Solution), a mathematical method that measures the Euclidean distance, to measure the positive ideal solution (PIS) and the negative ideal solution (NIS), the latter also called anti-ideal (Salabun et al., 2020). The final solutions will be as advantageous as they are close to the positive ideal solution, while they will be disadvantageous if close to the NIS. In the MCDA analysis, weights are defined for each indicator (Gaspars-Wieloch, 2023), considering five different scenarios reported in Table 8. The sum of weights for each scenario is equal to the unit value.

The objective of this weighting is to highlight the stability of the study, so the MCDA analysis is not aimed at changing the classification of alternatives, but at ensuring the overall stability of the study itself.

The scenarios outline stakeholder perspectives through the weighting of indicators, allowing the generation of conclusive rankings for each scenario (Kalbar et al., 2012). These rankings more accurately reflect stakeholder preference. In consideration of this, five scenarios (S1-S5) were identified and defined, each characterized by the variation in the weights associated with specific types of indicators, thus representing the differentiated preferences of the various stakeholders (Niero and Kalbar, 2019).

In scenario S1, all indicators are weighted in the same way. In the second scenario, circularity factors are given more weight, while in the third scenario, weights are assigned more to LCA indicators. The last two scenarios provide a higher preponderance for MCI, HH and MRS and EQ respectively. The steps of the TOPSIS method are reported in the work of Borawska, 2014. First, it proceeds with the creation of a standardized decision matrix, the normalized value of r_{ij} is equal to Eq. (6):

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^m a_{ij}^2}}, \text{ with } j = 1, \dots, n \quad (6)$$

where a_{ij} refers to the value of the j-th indicator, with respect to the i-th alternative considered.

At this point you introduce the weights for each indicator j-th w_j , in such a way that $\sum_{j=1}^n w_j = 1$ and results, according to Eq. (7):

$$v_{ij} = w_j a_{ij} \quad (7)$$

This way it is possible to calculate the weighted standardized decision matrix, where v_{ij} is the weighted normalized value. Determination of ideal and anti-ideal solutions can be found according to the Eqs. (8) and (9):

Table 8

Weights identified for each indicator and for the five scenarios considered (S1, S2, S3, S4 and S5).

Scenario	Material reutilization score	Material circularity indicator	Human health	Ecosystem quality
S1	0.25	0.25	0.25	0.25
S2	0.30	0.30	0.20	0.20
S3	0.20	0.20	0.30	0.30
S4	0.20	0.30	0.30	0.20
S5	0.30	0.20	0.20	0.30

$$A^+ = \{v_1^+, \dots, v_n^+\} = \left(\max_i v_{ij} \right) \quad (8)$$

$$A^- = \{v_1^-, \dots, v_n^-\} = \left(\min_i v_{ij} \right) \quad (9)$$

It is then calculated the measure of the distance, exploiting the Euclidean distance, through Eq. (10) the distance from the solution from the ideal solution can be expressed:

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (10)$$

The distance from the anti-ideal solution is calculated according to Eq. (11):

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (11)$$

Finally, the calculation of the proximity relative to the ideal solution can be expressed according to Eq. (12), this formula combines the two distances from the idea and anti-ideal solution:

$$CC_i^+ = \frac{d_i^-}{d_i^+ + d_i^-} \quad (12)$$

4. Results and discussion

4.1. Evaluation of data quality

The data was evaluated using the ILCD method and applied to aluminum, polypropylene, bioplastic industrial and home compost capsules respectively. Table 9 shows the results of the data quality analysis for the aluminum capsule. In the case of TeR, GR and C the data are of very high quality, as they come from data from companies working with the same materials and technologies. In addition, the data refer to the specific area being analyzed and come from all representative sites for the market concerned.

As regards indicators P and TiR, they are 2 and 3 respectively. In the first case, according to the ILCD method, the uncertainty is estimated between 7 % and 10 %, while for the second, the data are based on a set with an interval of <10 years. Requirement M also shows a high quality, as the data is verified based on measurements. Eq. (13) calculates the value of the DQR for the aluminum capsule, between 2 and 3, thus showing an excellent quality of data.

$$DQR_{Aluminum} = \frac{1 + 1 + 3 + 1 + 2 + 1 + 3 \cdot 4}{6 + 4} = 2.1 \quad (13)$$

In the case of the polypropylene capsule, the results of the data quality analysis is shown in Table 10.

Factors M and C have very high data quality levels, as they are data verified by measurements and come from the relevant representative market sites. Also, in this case TiR has a quality rate of 3, as the data set refers to a time interval of <10 years. TeR and GR instead have a quality rate of 2, as it refers to companies other than those in the case study, but working with the same materials and technologies and the data refer to a

Table 9

Data quality level and rate for the aluminum capsule.

Quality requirement	Quality level	Quality rate
Technological representativeness (TeR)	Very high quality	1
Geographical representativeness (GR)	Very high quality	1
Temporal representativeness (TiR)	Satisfactory quality	3
Completeness (C)	Very high quality	1
Parameter uncertainty (P)	High quality	2
Methodological appropriateness and consistency (M)	Very high quality	1

Table 10

Data quality level and rate for the polypropylene capsule.

Quality requirement	Quality level	Quality rate
Technological representativeness (TeR)	High quality	2
Geographical representativeness (GR)	High quality	2
Temporal representativeness (TiR)	Satisfactory quality	3
Completeness (C)	Very high quality	1
Parameter uncertainty (P)	High quality	2
Methodological appropriateness and consistency (M)	Very high quality	1

wider area than the geographical area analyzed. Eq. 14 shows the DQR for the polypropylene capsule.

$$DQR_{Polypropylene} = \frac{2 + 2 + 3 + 1 + 2 + 1 + 3 \cdot 4}{6 + 4} = 2.3 \quad (14)$$

The data quality rate in the case of the polypropylene capsule turns out to be optimal of little superior to that of the aluminum. Table 11 shows the level of data quality to produce the capsule in bioplastic industrial compost. TeR, GR and M have a quality rate of 1 indicating high data quality. C, on the other hand, has a quality rate of 3, as the data are representative only of some sites (<50 %) for the market considered. In this case the uncertainty parameter is 3, as the uncertainty fluctuates between 10 % and 25 %. The Eq. (15) shows the calculation of DQR for bioplastic industrial compost, which is higher than both aluminum and polypropylene.

$$DQR_{Industrial_Compost} = \frac{1 + 1 + 3 + 3 + 3 + 1 + 3 \cdot 4}{6 + 4} = 2.4 \quad (15)$$

In the case of home compost bioplastics, as can be seen from the Table 12, no data with a very high-quality level is available. The best values refer to TeR and GR, with a quality rate of 2. In this context, the data come from different companies that use similar technologies and cover a wider geographical area than the study. M and P also have a quality rate of 2, since the data are partially verified through measurements, while the uncertainty considered varies between 7 % and 10 %. On the other hand, lorries and C show low but satisfactory quality rates. The Eq. (16) shows the calculation of the DQR, which is equal to 2.6.

DQR analysis shows that for aluminum, polypropylene and bioplastic industrial compost the data quality is high, with a quality rate between 2.1 and 2.4, while for home bioplastic compost the data quality is lower, but still acceptable.

$$DQR_{Home_Compost} = \frac{2 + 2 + 3 + 3 + 2 + 2 + 3 \cdot 4}{6 + 4} = 2.6 \quad (16)$$

4.2. Circular footprint formula results

To solve the CFF it is necessary to go and define the factors present in Eqs. (2), (3) and (4). The **A** factor, according to the PEF Guide is between

Table 11

Data quality level and rate for the industrial compost capsule.

Quality requirement	Quality level	Quality rate
Technological representativeness (TeR)	Very high quality	1
Geographical representativeness (GR)	Very high quality	1
Temporal representativeness (TiR)	Satisfactory quality	3
Completeness (C)	Satisfactory quality	3
Parameter uncertainty (P)	Satisfactory quality	3
Methodological appropriateness and consistency (M)	Very high quality	1

Table 12

Data quality level and rate for the home compost capsule.

Quality requirement	Quality level	Quality rate
Technological representativeness (TeR)	High quality	2
Geographical representativeness (GR)	High quality	2
Temporal representativeness (TiR)	Satisfactory quality	3
Completeness (C)	Satisfactory quality	3
Parameter uncertainty (P)	High quality	2
Methodological appropriateness and consistency (M)	High quality	2

0.2 and 0.8, to consider both the effects of recycling, both in terms of recycled content and recyclability. In this study, the **A** factor was considered to be 0.2, so the avoided costs of recycling aluminum, polypropylene and bioplastics were accounted for with an allocation factor of 80 % (Bassani et al., 2024). The allocation factor **B**, inherent in the energy recovered during the incineration process, is considered equal to zero by default, so-called **R1**, as the raw materials considered are 100 % virgin. The quality ratio $\frac{Q_{sin}}{Q_p}$, $\frac{Q_{Sout}}{Q_p}$ of recycled content and recyclable material are by default 1 (European Commission, 2013). Factors **R2** e **R3** respectively refer to the proportions of the material in the product that will be recycled or used for energy recovery respectively.

In the Table 13 values are reported for the CF formula for each material and scenario considered (landfill, incineration, recycling and composting for bioplastics). **LVH** is calculated based on the lower heating value of the material, while $X_{ER,heat}$ and $X_{ER,elec}$ refer to the recovery efficiency of both Thermal and Electrical, respectively of 75 % and 30 %.

For the landfill scenario the factors shown in Table 13 are all equal to zero, therefore recitals (2), (3) and (4) the only factors to consider are the vectors E_v and E_D . The same applies to bioplastics and composting. For recycling the only factor other than zero is **R2** and therefore the carrier to be considered, in addition to E_v and E_D , is $E_{recyclingEoL}$. For incineration only the factor **R2** is zero, since plant efficiencies in terms of heat and electricity are present in the other terms, so in addition to E_v e E_D , the vector E_{ER} will be considered.

Table 13

Factors R2, R3, $X_{ER,heat}$, $X_{ER,elec}$ and LVH.

Aluminum	R2	R3	LVH x $X_{ER,heat}$ (MJ/kg)	LVH x $X_{ER,elec}$ (MJ/kg)
Landfill	0	0	0	0
Incineration	0	0.05	15	6
Recycling	0.67	0	0	0
Polypropylene	R2	R3	LVH x $X_{ER,heat}$	LVH x $X_{ER,elec}$
Landfill	0	0	0	0
Incineration	0	0.41	30	12
Recycling	0.45	0	0	0
Bioplastic Industrial Compost	R2	R3	LVH x $X_{ER,heat}$	LVH x $X_{ER,elec}$
Landfill	0	0	0	0
Incineration	0	0.08	15	6
Recycling	0.10	0	0	0
Composting	0	0	0	0
Bioplastic Home Compost	R2	R3	LVH x $X_{ER,heat}$	LVH x $X_{ER,elec}$
Landfill	0	0	0	0
Incineration	0	0.08	15	6
Recycling	0.10	0	0	0
Composting	0	0	0	0

For the four materials considered in the analysis are reported in Tables 14 and 15 the factors E_v e E_D , by convention considering negative inputs and positive outputs.

Tables 16 and 17 show the values of the vector elements $E_{recyclingEoL}$ e E_{ER} .

4.3. Impact and damage assessment of aluminum capsules

Fig. 6 shows the characterization of the impacts for the aluminum capsule, highlighting how the production process can have a high impact for all the categories examined, with percentages ranging from 9.71 % for the LO category to 96.8 % for the HT-C category, due of emissions due to the bauxite extraction process. In the CC-HH category the impact of the production process amounts to 81 % due to carbon dioxide emissions and the consumption of electricity and natural gas due to the use of ovens.

In the aluminum production process, other categories with a high impact include HT-NC, PMF and CC-H, with percentages of 93.8 %, 86.3 % and 80.3 % respectively. These impacts are mainly due to electricity consumption and slag production during aluminum heating. In addition, the FA and TA categories have significant impacts, with percentages of 87.1 % and 86.4 %, due to emissions of sulfur dioxide and nitrogen dioxides in the bauxite extraction process. In aluminum production, intermediate impacts are evident in the IR-EQ and IR-HH categories, representing respectively 71.3 % and 72.6 % of the total impact, due to heat generation and electricity consumption. The LT and TP categories contribute 75.3 % and 76.2 % of the total impact, mainly due to the exploitation of the territory for the extraction of raw materials and the use of cooling water to regulate the temperature of chemical reactors. The categories with minor impacts in the aluminum production process include OLD, WA-TE and LO, with impact percentages of 44.9 %, 47.3 % and 9.71 %, respectively. These impacts stem mainly from the use of natural gas and aluminum hydroxides in bauxite. Rolling, on the other hand, has no particular influence on the life cycle of the product, except for the FE category where the impact is 11.4 %, due to the consumption of lubricants during the process. The decontamination process also has impacts from 4 % to 21 %, excluding the OLD category with 41.1 % due to the use of steam. Secondary packaging in corrugated cardboard does not present particular impacts except for the ME, FEU and LO categories with 30.3 %, 52.4 % and 88.2 %, respectively. The impacts in these

Table 14

Factor E_D for Aluminum, Polypropylene, Industrial and Home compost capsule

E_v elements	
Aluminum	
Aluminum primary liquid (g)	−0.95
Argon (g)	−1.5 × 10 ^{−2}
Electricity, medium voltage (Wh)	−10.0529
Heat, district or industrial, natural gas (J)	−0.89
Polypropylene	
Propylene (g)	−0.98
Ethylene (g)	−5.45 × 10 ^{−2}
Heat (MJ)	−0.05
Electricity, medium voltage (Wh)	−0.35
Industrial compost	
Polybutylene succinate granulates (g)	−2.088
Polybutylene adipate-co-terephthalate granulates (g)	−0.486
Talc (g)	−0.3
Electricity (Wh)	−1.65
Home compost	
Polybutylene succinate granulates (g)	−0.48
Poly-3-hydroxybutyrate-co-3-hydroxyhexanoate (g)	−1.92
Talc (g)	−0.549
Electricity (Wh)	−1.65

Table 15Factor E_D for Aluminum, Polypropylene, Industrial and Home compost capsule

E_D elements	
Aluminum	
Transport freight lorry 16–32 ton (kgkm)	−0.015
Transport freight lorry 16–32 ton (kgkm)	−0.244
Carbon dioxide (g)	1.22×10^{-3}
Methane (g)	3.7×10^{-4}
Polypropylene	
Transport freight lorry 16–32 ton (kgkm)	−0.040
Transport freight lorry 16–32 ton (kgkm)	−0.702
Carbon dioxide (g)	3.24×10^{-3}
Methane (g)	6.48×10^{-5}
Industrial compost	
Transport freight lorry 16–32 ton (kgkm)	−0.015
Transport freight lorry 16–32 ton (kgkm)	−0.253
Carbon dioxide (g)	1.62×10^{-4}
Methane (g)	3.24×10^{-5}
Home compost	
Transport freight lorry 16–32 ton (kgkm)	−0.015
Transport freight lorry 16–32 ton (kgkm)	−0.253
Carbon dioxide (g)	1.62×10^{-4}
Methane (g)	3.24×10^{-5}

Table 16Factor $E_{\text{recyclingEoL}}$ for Aluminum, Polypropylene, Industrial and Home compost capsule

$E_{\text{recyclingEoL}}$ elements	
Aluminum	
Transport freight lorry 16–32 ton (kgkm)	-1.14×10^{-4}
Transport freight lorry 16–32 ton (kgkm)	-6.31×10^{-3}
Electricity (Wh)	−0.57
Recovered Aluminum (g)	0.71
Polypropylene	
Transport freight lorry 16–32 ton (kgkm)	-2×10^{-3}
Transport freight lorry 16–32 ton (kgkm)	-5×10^{-5}
Electricity (Wh)	−1.62
Polypropylene granulates (g)	1.5
Industrial compost	
Transport freight lorry 16–32 ton (kgkm)	-6.78×10^{-4}
Transport freight lorry 16–32 ton (kgkm)	-4.07×10^{-2}
Electricity (Wh)	−0.12
Home compost	
Transport freight lorry 16–32 ton (kgkm)	-6.78×10^{-4}
Transport freight lorry 16–32 ton (kgkm)	-4.07×10^{-2}
Electricity (Wh)	−0.12

categories are essentially due to deforestation, land occupation and the production of Kraft paper. Transport appears to be irrelevant with impacts that do not exceed 3 %. The end of life, however, determines benefits in 20 out of 21 categories, due to the high percentage of aluminum recycling. The end of life appears to have an impact only in the POF category (8.11 %), due to the emission of carbon dioxide and monoxide during incineration. Fig. 7 shows the normalization of the impacts which confirms the results obtained in the characterization phase. The EQ category is the one that presents the greatest damage, for the aluminum production process, followed by rolling and the production of secondary packaging. The end of life instead provides benefits in the EQ category. In HH the only process that causes damage, even if to a limited extent, is the aluminum production process, while for the other

Table 17Factor E_{ER} for Aluminum, Polypropylene, Industrial and Home compost capsule

E_{ER} elements	
Aluminum	
Oxygen (g)	-1.9×10^{-3}
Ammonia (m ³)	-6.75×10^{-7}
Carbon dioxide (g)	3.41×10^{-2}
Heat, waste (J)	21.6
Polypropylene	
Oxygen (g)	-4.02×10^{-3}
Ammonia (m ³)	-2.18×10^{-4}
Carbon dioxide (g)	2.68×10^{-2}
Heat, waste (J)	9.31
Industrial compost	
Oxygen (g)	-2×10^{-3}
Ammonia (m ³)	-1.34×10^{-4}
Carbon dioxide (g)	1.32×10^{-2}
Heat, waste (J)	8.64×10^{-7}
Home compost	
Oxygen (g)	-2×10^{-3}
Ammonia (m ³)	-1.34×10^{-4}
Carbon dioxide (g)	1.32×10^{-2}
Heat, waste (J)	8.64×10^{-7}

processes there is no obvious damage.

Tables 18 and 19 show the numerical values of the impact characterization and normalization for the aluminum capsule. In Astarita et al. (2023) the environmental impacts of aluminum cans are assessed, confirming how the aluminum extraction process, as well as energy consumption, has a significant environmental impact throughout the life cycle. Wang (2020) instead highlighted how the extraction of aluminum, compared to the extraction of raw materials for plastic and glass, was characterized by high carbon dioxide emissions.

4.4. Impact and damage assessment of polypropylene capsules

Fig. 8 shows the characterization of the impacts relating to the life cycle of the polypropylene capsule, while Table 20 shows the numerical values of this characterization. Similarly, to what was seen for aluminum, the production of the raw material, in this case polypropylene granulate, has a considerable impact in all categories with variations between 23.8 % and 96.3 %. WA-FE and HT-C are the most impacted categories due to oil extraction and water usage within the process. Extrusion does not create particular impacts on the life cycle, except for the IR-HH category, with 18.7 %. Molding, on the other hand, has a greater impact on the TPW category due to the consumption of electricity during the process. For the other categories the impacts do not exceed 7 %. Decontamination has important impacts in the WA-TE category (16.2 %) for the consumption of water and disinfectant substances. The production of secondary packaging has a high impact on the IR-HH and PMF categories, as it is made up of aluminum and polypropylene and a third layer of polyester. Therefore, both the production processes of the virgin materials and the three-layer lamination process are taken into account.

The end of life provides benefits especially in the FEU category (−72.8 %), due to the presence of a good recycling rate (45 %) and heat recovery through incineration. The only category where the end-of-life phase has a significant impact is POF (98.2 %) due to the substances released by the waste-to-energy process. Transport does not appear to be particularly influential, with a percentage that does not exceed 4 %. Fig. 9 shows the normalization of the impacts which confirms the results obtained previously. In the HH category, the only process that causes significant damage is that of granulate production, as in the case of EQ, where, however, the end of life is also present. Table 21 shows the

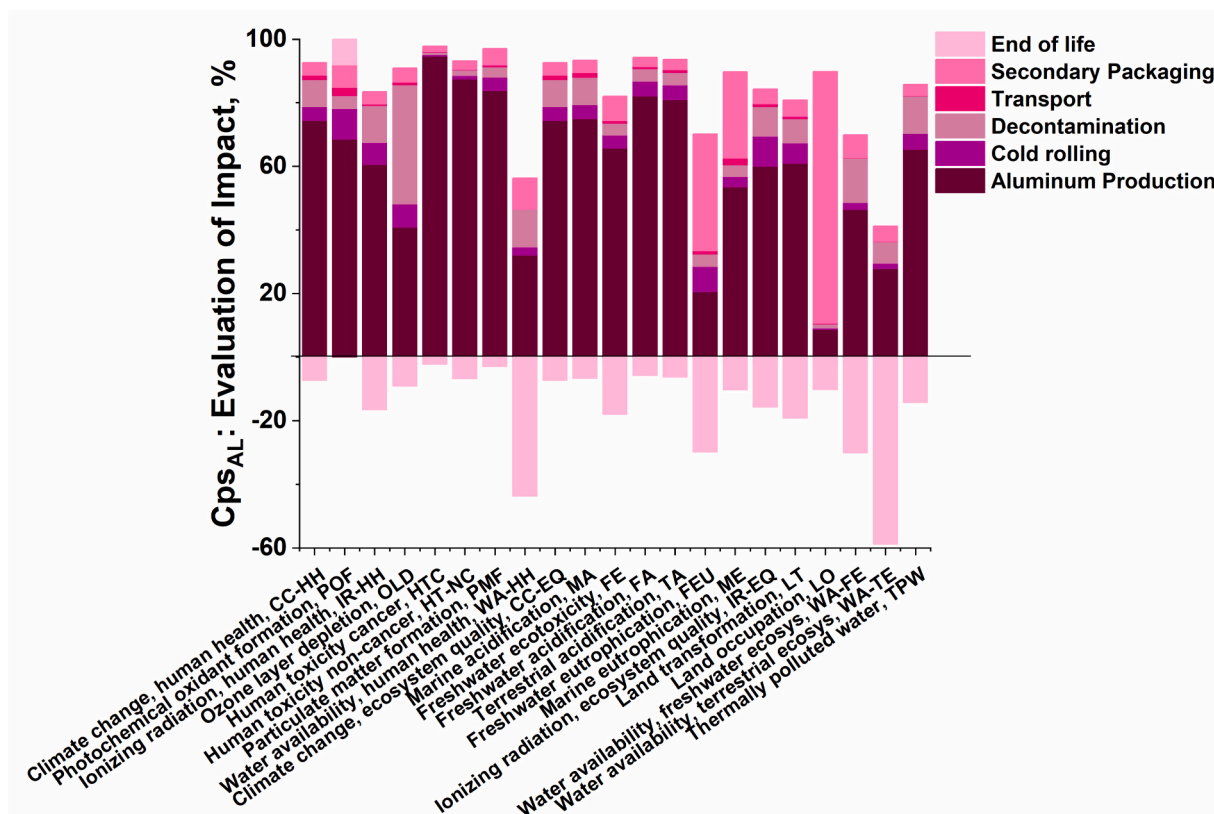


Fig. 6. Characterization of aluminum capsule (Cps_{AL}) impacts.

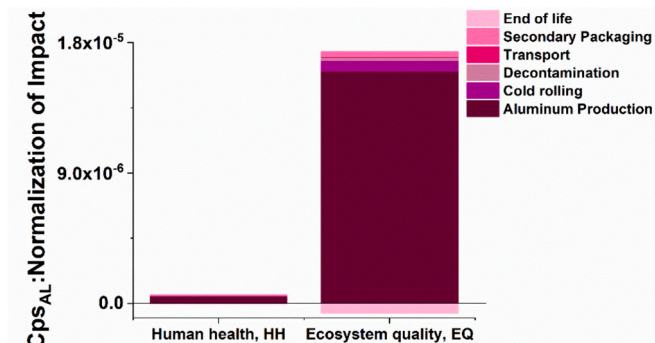


Fig. 7. Normalization of aluminum capsule (Cps_{AL}) impacts.

numerical values of the normalization. Moretti et al. (2020) analyzed how polypropylene has impacts in the CC-HH category of 62 %, much higher than the bio-based counterpart for which they drop to 40 %. Antelava et al. (2019) have demonstrated how thermo-mechanical recycling is advantageous compared to landfill disposal and incineration. Bora et al. (2020) instead, they analyzed five different disposal methods for propylene, showing how mechanical recycling is more eco-friendly than pyrolysis and gasification.

4.5. Evaluation of the impacts and damage of capsules in home compost

Fig. 10 shows the histogram of the impacts of the life cycle of the capsule made of home-compost material. Compared to the aluminum and polypropylene equivalent, the granule production process is less significant from an impact point of view, with percentages varying between 0.76 % and 58.3 %. The categories most involved are those of POF and LO due to the processing of sugar cane molasses production waste

and the use of water and electricity. Extrusion does not cause significant impacts, except for the IR-HH, IR-EQ and TPW categories with an amount of 23.5 %, 22.3 % and 17.6 %, respectively, due to the consumption of electricity during the process. For the other categories the impacts do not exceed 10 %. The same considerations can be applied to the molding process, in this case the categories most affected are LT and LO with 63.4 % and 45.1 %, due to the use of tertiary packaging for the transport of granules from one machine to another. The OLD category is the only one in which the decontamination process appears to have significant impacts, with a percentage of 32.6 %. In other cases, the impacts are not very significant, with values not exceeding 9 %.

In the case of home-compost capsules, the most significant process, therefore, is the production of the secondary packaging, in particular of the triple aluminum, polypropylene and polyester. The impacts vary between 10 % and 91 %, with higher values in FE, WA and HT-C with 87.4 %, 82.4 % and 90.9 % respectively due to the production of the laminates and the heat-sealing process. Decontamination excluding the OLD category (32.6 %) does not have high impacts in the remaining categories. Likewise, transport does not exceed 5 % in all categories. Compared to other cases, the end of life does not present obvious benefits, except for LO and FEU (−5.43 %, −23.7 %). This aspect is due to the emissions of NH_4 and N_2O and CO_2 into the air, as well as CH_4 and water. The FA and TA categories present impacts of 84.8 % and 86.3 % respectively, due to land occupation and oxygen used in the home composting process.

Tables 22 and 23 show the numerical results of the characterization and normalization respectively for the capsule in home compost. Fig. 11 shows the evaluation of the normalized damage of the life cycle of the capsule in domestic compost bioplastic, which confirms the results obtained in the impact evaluation. The production of secondary packaging appears to be the process that creates the most damage, both in terms of ecosystem quality and human health. The impacts of polyhydroxyalkanoates (PHA) with improved barrier properties were

Table 18
Numerical values of impact characterization for the aluminum capsule

Impact categories	Units	Aluminum production	Cold rolling	Decontamination	Transport	Secondary packaging	End of life	Total
Climate change, human health, short term, CC-HH	kg CO ₂ eq	5.19×10^{-9}	3.00×10^{-10}	5.93×10^{-10}	9.45×10^{-11}	2.85×10^{-10}	-5.12×10^{-10}	5.95×10^{-10}
Photochemical oxidant formation, POF	kg NMVOC eq	8.95×10^{-13}	1.25×10^{-13}	5.50×10^{-14}	3.32×10^{-14}	9.18×10^{-14}	1.06×10^{-13}	1.31×10^{-12}
Ionizing radiation, human health, IR-HH	Bq C-14 eq	7.91×10^{-12}	8.96×10^{-13}	1.52×10^{-12}	5.82×10^{-14}	5.11×10^{-13}	-2.16×10^{-12}	8.74×10^{-12}
Ozone layer depletion, OLD	kg CFC-11 eq	4.17×10^{-13}	7.56×10^{-14}	3.82×10^{-13}	8.61×10^{-15}	4.54×10^{-14}	-9.32×10^{-14}	8.35×10^{-13}
Human toxicity cancer, short term, HTC	CTUh	4.68×10^{-9}	2.55×10^{-11}	3.87×10^{-11}	5.08×10^{-12}	8.52×10^{-11}	-1.09×10^{-10}	4.73×10^{-9}
Human toxicity cancer, short-term HT-NC	CTUh	1.90×10^{-9}	2.34×10^{-11}	4.10×10^{-11}	3.32×10^{-12}	5.83×10^{-11}	-1.48×10^{-10}	1.88×10^{-9}
Particulate matter formation PMF	kg PM _{2.5} eq	5.00×10^{-9}	2.48×10^{-10}	1.97×10^{-10}	2.98×10^{-11}	3.16×10^{-10}	-1.74×10^{-10}	5.62×10^{-9}
Water availability, human health, WA-HH	m ³ consumed	9.72×10^{-12}	7.66×10^{-11}	3.60×10^{-10}	4.01×10^{-15}	3.00×10^{-10}	-1.33×10^{-9}	3.79×10^{-10}
Climate change, quality of ecosystems, in short CC-EQ	kg CO ₂ eq	0.001	6.49×10^{-5}	1.28×10^{-4}	2.04×10^{-5}	6.17×10^{-5}	-1.11×10^{-4}	1.28×10^{-3}
Marine acidification, short term, MA	kg SO ₂ eq	9.58×10^{-5}	5.74×10^{-6}	1.09×10^{-5}	1.84×10^{-6}	5.07×10^{-6}	-8.48×10^{-6}	1.11×10^{-4}
Freshwater ecotoxicity, short term, FE	CTUe	8.07×10^{-5}	5.03×10^{-6}	4.67×10^{-6}	9.11×10^{-7}	9.44×10^{-6}	-2.21×10^{-5}	7.87×10^{-5}
Freshwater acidification, FA	kg SO ₂ eq	9.74×10^{-5}	5.48×10^{-6}	4.68×10^{-6}	8.20×10^{-7}	3.44×10^{-6}	-6.80×10^{-6}	1.05×10^{-4}
Terrestrial acidification, TA	kg SO ₂ eq	6.16×10^{-4}	3.48×10^{-5}	3.02×10^{-5}	6.28×10^{-6}	2.55×10^{-5}	-4.82×10^{-5}	6.65×10^{-4}
Freshwater eutrophication, FEU	kg PO ₄ P-lim eq	3.21×10^{-7}	1.25×10^{-7}	6.05×10^{-8}	1.48×10^{-8}	5.74×10^{-7}	-4.66×10^{-7}	6.29×10^{-7}
Marine eutrophication, ME	kg N N-lim eq	5.19×10^{-6}	3.15×10^{-7}	3.56×10^{-7}	2.03×10^{-7}	2.64×10^{-6}	-9.95×10^{-7}	7.71×10^{-6}
Ionizing radiation, ecosystem quality, IR-EQ	Bq C – 14 eq	6.73×10^{-13}	1.05×10^{-13}	1.05×10^{-13}	9.51×10^{-15}	5.18×10^{-14}	-1.76×10^{-13}	7.68×10^{-13}
Land transformation, biodiversity, LT	m ² arable land	1.82×10^{-4}	1.94×10^{-5}	2.26×10^{-5}	2.24×10^{-6}	1.53×10^{-5}	-5.73×10^{-5}	1.84×10^{-4}
Land occupation, biodiversity, LO	m ² arable land x yr	5.3×10^{-5}	2.74×10^{-6}	7.82×10^{-6}	7.90×10^{-7}	4.83×10^{-4}	-6.24×10^{-5}	4.85×10^{-5}
Water availability, freshwater ecosystem., WA-FE	m ³ dissipated	1.07×10^{-8}	5.08×10^{-10}	3.20×10^{-9}	2.41×10^{-11}	1.64×10^{-9}	-6.92×10^{-9}	9.15×10^{-9}
Water availability, terrestrial ecosystem., WA-TE	m ³ dissipated	1.43×10^{-7}	8.79×10^{-9}	3.45×10^{-8}	3.15×10^{-10}	2.52×10^{-8}	-3.03×10^{-7}	-9.1×10^{-8}
Thermally polluted water, TPW	m ³ cooling water	9.91×10^{-9}	7.58×10^{-10}	1.78×10^{-9}	1.46×10^{-11}	5.42×10^{-10}	-2.16×10^{-9}	1.08×10^{-8}

Table 19
Numerical values of normalization for the aluminum capsule

Categories of damage	Units	Aluminum production	Cold rolling	Decontamination	Transport	Secondary packaging	End of life
Human health, HH	DALY	4.98×10^{-7}	2.37×10^{-8}	4.36×10^{-8}	6.26×10^{-9}	2.72×10^{-8}	-5.4×10^{-8}
Ecosystem quality, EQ	PDF.m ² .year	1.6×10^{-5}	7.25×10^{-7}	2.64×10^{-7}	1.86×10^{-8}	3.53×10^{-7}	-6.9×10^{-7}

examined in [Vea et al. \(2021\)](#), showing that raw materials are the main source of impact (up to 94 %). This is due to the use of molasses, traditionally used in the production of animal feed. However, the use of PHA has significant environmental benefits in the category of climate change.

In the study conducted by [Ibarretxe et al. \(2022\)](#), the environmental performance of poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) was evaluated in comparison to other fossil plastics, such as polypropylene, polyethylene terephthalate and polyamide. It has been observed that the adoption of this bioplastic involves a reduction of the impacts related to climate change, both in the case of composting and in the case of marine degradation. In contrast, petrochemical plastics, especially polyamide, show significant environmental impacts when landfilled.

4.6. Evaluation of the impacts and damages of capsules in industrial compost

[Fig. 12](#) shows the histogram of the impacts of the life cycle of the industrial compost capsule, while [Table 24](#) shows the numerical values

of the impacts. The granule production process showed higher impacts in the WA-TE and FE categories, respectively 85.4 % and 65.8 %. LO, LT and E have percentages that amount to 57.3 %, 51.8 % and 64.5 %, respectively. In the other cases, the impacts are lower with values that do not exceed 40 %. The impacts of the granule production process lead to higher impacts in all categories compared to the granule production process in domestic compost bioplastic, as it has a higher content of fossil plastic. The production of secondary packaging appears to be the most influential process from an impact point of view. Particularly, HT-C and FE categories show impacts of 83.3 % and 75 %, due to the production of the aluminum laminate. In the CC-HH and HT non-cancer category, the impacts are 48.2 % and 60.9 % respectively, while in the WA-HH category, the impact percentage is 59.9 %, due to the production of polypropylene and polyester. In the TPW category the impact is 40.3 %, due to the electricity consumption of the heat-sealing process. For the remaining categories the impacts are lower, ranging between 11.5 % and 35.3 %. The impacts of decontamination showed similar results compared to the case of home compost. The only category that highlights a significant impact is OLD with a percentage of 26.7 %, in

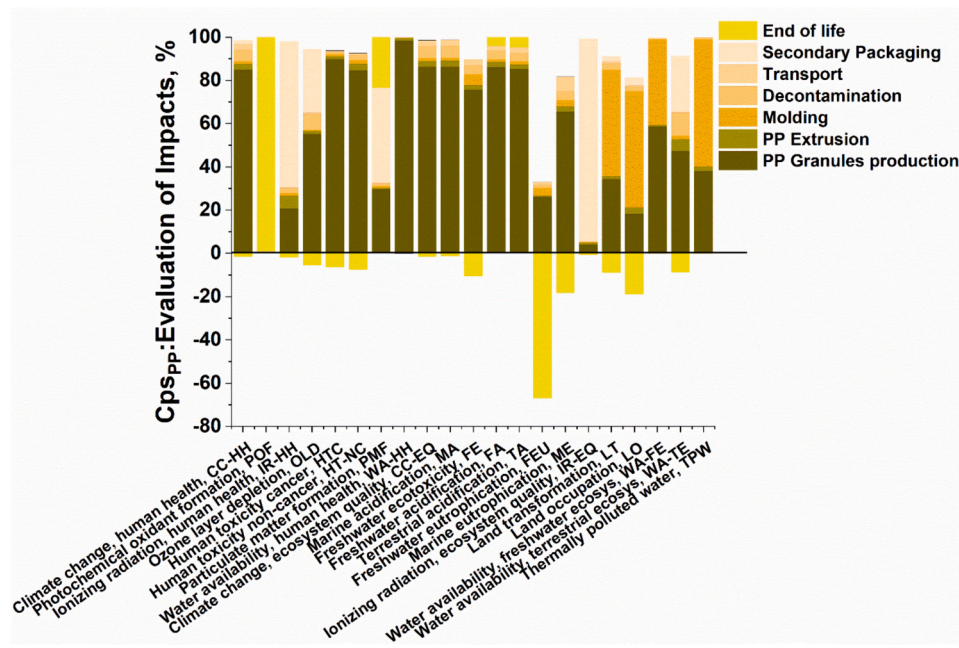


Fig. 8. Characterization of polypropylene capsule (Cs_{pp}) impacts.

other cases it does not exceed 7 %. The end of life presents notable benefits with negative impacts that vary from a minimum of -3.97% and -92.8% , due to the presence of industrial composting, as the output of the process is the production of compost and therefore phosphorus-based fertilizer. For the WA-HH and FEU categories the benefits are -79.9% and -69% , due to water, phosphorus and phosphoric acid emissions. As regards, the environmental impacts of the end of life, FA and TA categories have impacts of 81.2% and 82.9% respectively, due to incineration emissions. The POF category has an impact of 90.7% , due to the fuel used to transport waste to the waste-to-energy plant and particulate emissions smaller than $10\text{ }\mu\text{m}$, which can cause serious damage to human health. Transport has no significant impacts meaning that they do not exceed the percentage of 3.48% . Extrusion has impacts of 11.6% and 11.9% for the IR-HH and TPW categories respectively, due to electricity consumption. In other cases, the values are not significant as they do not exceed 4% . For molding it is possible to repeat the same considerations as the previous case, with the only impacts (28%) being found in the IR-HH e IR-EQ categories.

Fig. 13 shows the normalization of the damage which confirms the results obtained in the characterization phase. In general, the overall normalized damages in both HH and EQ are higher than home compost, but lower than aluminum and polypropylene, with values of 1.35×10^{-5} for EQ and 6.09×10^{-7} for HH. Table 25 highlights the numerical values of damage normalization.

Atiwesh et al. (2021) analyzed the damage caused by bioplastics and fossil plastics. In some cases, the bioplastic is disposed of directly in landfill, causing methane emissions. The damage caused by conventional plastics are however more harmful.

In the study conducted by [Rattana and Gheewala \(2019\)](#) it is noted that the production of polylactic acid shopper bags generates significant impacts in the categories of eutrophication and acidification, both during the cultivation of sugar cane, both in the bioplastic resin production process. On the contrary, in the case of bags made of high-density polyethylene, there are major impacts resulting from the extraction and production of oil and ethylene, in the categories of fossil fuel exhaustion and acidification.

4.7. Comparison based on the current disposal scenario

Fig. 14 shows the results of the three alternatives in the case of the

current disposal scenario. The polypropylene capsule is the most impactful for 14 out of 21 categories. This result is mainly attributable to the fact that polypropylene is a material of fossil origin. As a result, the process of extraction and refining of oil necessary for the production of the raw material has a significant impact on these categories. In addition, another determining factor is the mass of polypropylene capsules, which is approximately three times greater than that of aluminum capsules. Polypropylene capsule needs to be packaged using triple layer packaging and, accordingly, the production of the aluminum, polypropylene and polyester layers must be considered. The FE category provides 100 % benefits for polypropylene, due to the high percentage of recycling, which has made it possible to save significantly on the oil and natural gas used. In the ME, LO, FEU and HT categories, the aluminum capsule causes greater impacts due to the aluminum production process, due to the emissions of nitrogen oxides and nitrates present during the extraction process of the raw material. Furthermore, the impact is also generated by the production of secondary packaging in corrugated cardboard. Capsule in industrial compost biopolymer has the greatest impact in the FE and WA-FE categories, due in part to composting and compost production, as well as the use of water to produce waste from corn cultivation. Capsule in home compost biopolymer is the best alternative in all categories. Home composting is less impactful than industrial composting. Additionally, home composting requires lower amounts of resource and land use, resulting in reduced emissions of nitrous monoxide, methane and carbon dioxide.

Fig. 15 shows the normalization of the impacts which confirm the values obtained in the characterization phase. In the EQ category, aluminum capsules create the most damage, while home compost biopolymer represents the best alternative. In HH, polypropylene is the most harmful alternative, on the contrary, aluminum has lower impacts than polypropylene, but slightly higher than the home compost and industrial compost biopolymer of 9 % and 13 %, respectively. In the study conducted by [Tonelli et al. \(2019\)](#), polypropylene capsules are identified as the least favorable option, followed by aluminum and polylactic acid capsules. This evaluation takes into account the production of secondary packaging, made of fossil and non-recycled material.

Table 20
Impact characterization numerical values for the polypropylene (PP) capsule

Impact categories	Units	Production of PP granules	PP extrusion	Molding	Decontamination	Transport	Secondary packaging	End of life	Total
Climate change, human health, short term, CC-HH	kg CO2 eq	8.80×10^{-9}	2.75×10^{-10}	1.42×10^{-10}	5.65×10^{-10}	2.67×10^{-10}	1.68×10^{-10}	-1.5×10^{-10}	-1.08×10^{-8}
Photochemical oxidant formation, POF	kg NMVOC eq	1.11×10^{-12}	2.8×10^{-14}	2.0×10^{-14}	5.24×10^{-14}	9.43×10^{-14}	3.59×10^{-13}	1.72×10^{-10}	1.67×10^{-12}
Ionizing radiation, human health, IR-HH	Bq C-14 eq	1.25×10^{-11}	3.43×10^{-12}	8.26×10^{-13}	1.45×10^{-12}	1.6×10^{-13}	4.04×10^{-11}	-1.1×10^{-12}	5.77×10^{-11}
Ozone layer depletion, OLD	kg CFC-11 eq	2.64×10^{-12}	7.09×10^{-14}	2.15×10^{-14}	3.64×10^{-13}	2.36×10^{-14}	1.40×10^{-12}	-2.7×10^{-13}	4.52×10^{-12}
Human toxicity cancer, short term, HTC	CTUh	3.03×10^{-9}	4.04×10^{-11}	3.85×10^{-11}	3.69×10^{-11}	1.39×10^{-11}	2.15×10^{-14}	-2.1×10^{-10}	3.16×10^{-9}
Human toxicity cancer, short-term HT-NC	CTUh	1.31×10^{-9}	4.49×10^{-11}	2.65×10^{-11}	3.91×10^{-11}	9.17×10^{-12}	1.19×10^{-13}	-1.2×10^{-10}	1.31×10^{-9}
Particulate matter formation PMF	kg PM2.5 eq	5.00×10^{-9}	1.15×10^{-10}	1.34×10^{-10}	1.87×10^{-10}	8.34×10^{-11}	7.37×10^{-9}	3.95×10^{-9}	1.29×10^{-8}
Water availability, human health, WA-HH	m ³ consumed	1.17×10^{-7}	1.38×10^{-9}	-1.7×10^{-11}	3.43×10^{-10}	-2.2×10^{-13}	1.34×10^{-10}	-4.2×10^{-11}	1.19×10^{-7}
Climate change, quality of ecosystems, in short CC-EQ	kg CO2 eq	1.90×10^{-3}	5.94×10^{-5}	3.08×10^{-5}	1.22×10^{-4}	5.79×10^{-5}	2.64×10^{-12}	-3.3×10^{-5}	2.14×10^{-3}
Marine acidification, short term, MA	kg SO ₂ eq	1.61×10^{-4}	5.15×10^{-6}	2.53×10^{-6}	1.04×10^{-5}	5.19×10^{-6}	4.49×10^{-11}	-2.2×10^{-6}	1.82×10^{-4}
Freshwater ecotoxicity, short term, FE	CTUe	7.75×10^{-5}	1.94×10^{-6}	5.19×10^{-10}	4.45×10^{-6}	2.53×10^{-6}	2.65×10^{-11}	-1.1×10^{-5}	8.06×10^{-5}
Freshwater acidification, FA	kg SO ₂ eq	9.64×10^{-5}	2.61×10^{-6}	1.4×10^{-6}	4.46×10^{-6}	2.32×10^{-6}	1.15×10^{-12}	0.005	1.07×10^{-4}
Terrestrial acidification, TA	kg SO ₂ eq	6.13×10^{-4}	1.68×10^{-5}	9.43×10^{-6}	2.88×10^{-5}	1.78×10^{-5}	1.34×10^{-10}	0.034	6.86×10^{-4}
Freshwater eutrophication, FEU	kg PO ₄ P-lim eq	9.18×10^{-7}	2.48×10^{-8}	1.2×10^{-7}	5.77×10^{-8}	4.04×10^{-8}	8.26×10^{-13}	-2.4×10^{-6}	-1.24×10^{-6}
Marine eutrophication, ME	kg N N-lim eq	5.64×10^{-6}	2.16×10^{-12}	2.61×10^{-7}	3.39×10^{-7}	5.77×10^{-7}	1.19×10^{-13}	-1.6×10^{-6}	5.43×10^{-6}
Ionizing radiation, ecosystem quality, IR-EQ	Bq C-14 eq	1.15×10^{-12}	2.09×10^{-13}	1.19×10^{-13}	1.00×10^{-13}	2.61×10^{-14}	2.65×10^{-11}	-2.1×10^{-13}	2.79×10^{-11}
Land transformation, biodiversity, LT	m ² arable land	2.39×10^{-4}	9.1×10^{-6}	3.42×10^{-4}	2.16×10^{-5}	6.11×10^{-6}	1.59×10^{-5}	-6.2×10^{-5}	5.72×10^{-4}
Land occupation, biodiversity, LO	m ² arable land x yr	6.27×10^{-5}	9.21×10^{-6}	1.82×10^{-4}	7.44×10^{-6}	2.16×10^{-10}	1.13×10^{-5}	-6.4×10^{-5}	2.11×10^{-4}
Water availability, freshwater ecosystem., WA-FE	m ³ dissipated	5.42×10^{-7}	7.37×10^{-9}	3.65×10^{-7}	3.04×10^{-9}	6.61×10^{-11}	5.58×10^{-9}	-1.3×10^{-9}	9.22×10^{-7}
Water availability, terrestrial ecosystem., WA-TE	m ³ dissipated	1.46×10^{-7}	1.66×10^{-8}	5.58×10^{-9}	3.28×10^{-8}	8.61×10^{-10}	7.98×10^{-8}	-2.7×10^{-8}	2.82×10^{-7}
Thermally polluted water, TPW	m ³ cooling water	7.98×10^{-9}	4.05×10^{-9}	1.23×10^{-7}	1.7×10^{-9}	4×10^{-11}	7.09×10^{-14}	-3.3×10^{-10}	2.08×10^{-7}

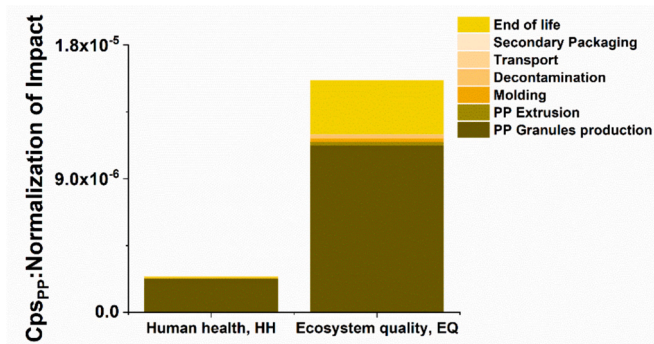


Fig. 9. Normalization of propylene capsule (Cps_{pp}) impacts.

4.8. Sensitivity analysis

4.8.1. Comparison based on the future disposal scenario

Fig. 16 shows the characterization of the impacts for the 2033 (ten years) disposal scenario, i.e. increasing the disposal percentages as far recycling for aluminum and polypropylene and composting for biopolymers are concerned.

The polypropylene capsule is confirmed to be the least sustainable alternative even in a hypothetical future scenario, except for the HT cancer and non-cancer, PMF, and ME categories, where aluminum capsule has a greater impact. Another category where aluminum capsule highlights greater impacts is LO, due to the production of secondary packaging for the transport of the capsule. FEU and WA-TE present benefits for polypropylene and aluminum capsule, respectively, due to the increase in the recycling rate. In FE and WA-TE, industrial compost capsule is the worst solution, as already seen in the current scenario. In the normalization in Fig. 17, the results obtained in the current scenario

are confirmed, except for the EQ category, in which aluminum capsule appears to be the worst alternative. In all cases, the capsule in home compost biopolymer, however, proves to be the most sustainable material.

4.8.2. Third disposal scenario with aluminum and 100% recycled polypropylene

In the analysis of the 2033 (ten years) disposal scenario, no major variations were found compared to the current disposal scenario. An extreme (third) disposal scenario must therefore be considered, with aluminum and polypropylene coming from 100 % recycled raw materials. As shown in Fig. 18, the aluminum capsule appears to have the greatest impact in 5 categories, in those of human toxicity, in ME and LO. However, aluminum recycling is a process with a high environmental impact, due to the processes carried out in the foundry, with the pretreatment led at 500 °C and the subsequent melting of the scrap at 800 °C. Brock and Williams (2020) analyzed some materials for the production of beverage packaging. Recycled aluminum was found to have a greater impact than polyethylene terephthalate (PET), a petrochemical plastic, in the ME categories, while it was the best choice in FE and CC, as confirmed by the present study. Also, for the polypropylene capsule there is a general improvement in impacts, except for the TP, WA-FE and IR-HH categories, due to the consumption of electricity during the mechanical recycling process.

Fig. 19 shows the normalization of the impacts. Compared to the previously hypothesized disposal scenarios, capsule in recycled polypropylene creates less damage in both HH and EQ. Capsule in home composting bioplastic is still competitive both for the type of disposal and for the higher percentage of organic raw material present. In Galve et al. (2022), the use of recycled polypropylene saw impacts decrease by 42.8 % and 29.8 % compared to virgin polypropylene, based on the ReCiPe and Carbon Footprint method, respectively. These results are

Table 21

Numerical values of normalization for polypropylene (PP) capsule.

Categories of damage	Units	Production of PP granulates	Extrusion	Molding	Decontamination	Transport	Secondary packaging	End of life
Human health, HH	DALY	2.26×10^{-6}	3.84×10^{-8}	1.09×10^{-8}	4.15×10^{-8}	1.76×10^{-8}	1.89×10^{-10}	4.27×10^{-8}
Ecosystem quality, EQ	PDF.m ² . year	1.12×10^{-5}	2.38×10^{-7}	2.27×10^{-7}	2.5×10^{-7}	5.18×10^{-8}	2.3×10^{-9}	3.57×10^{-6}

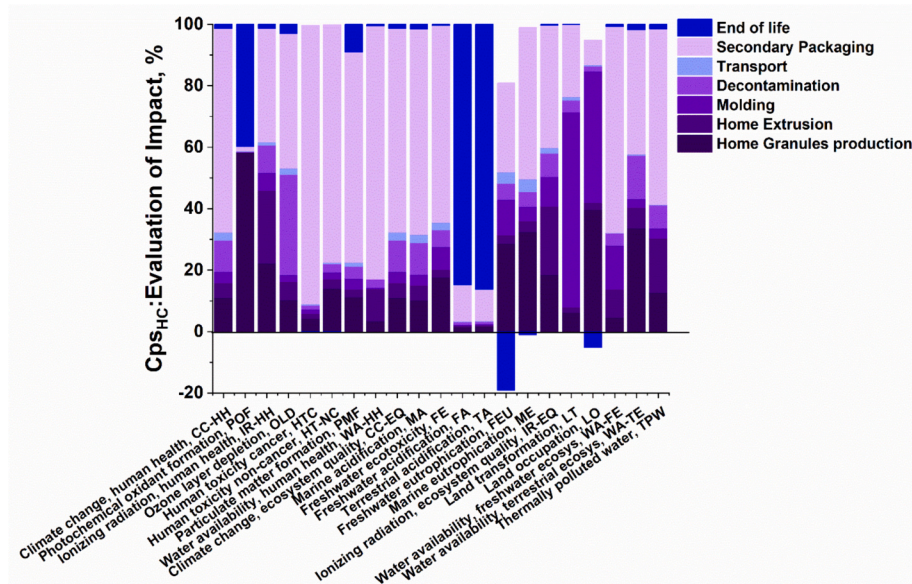


Fig. 10. Evaluation of home-compost biopolymer capsule (Cps_{HC}) impacts.

Table 22
Numerical values of impact characterization for the home-compost (HC) biopolymer capsule

Impact categories	Units	Production of HC granules	HC extrusion	Molding	Decontamination	Transport	Secondary packaging	End of life	Total
Climate change, human health, short term, CC-HH	kg CO2 eq	6.13×10^{-10}	2.61×10^{-10}	2.07×10^{-10}	5.65×10^{-10}	1.45×10^{-10}	3.68×10^{-9}	7.29×10^{-11}	5.54×10^{-9}
Photochemical oxidant formation, POF	kg NMVOC eq	2.46×10^{-11}	2.72×10^{-14}	3.83×10^{-14}	5.24×10^{-14}	4.68×10^{-14}	6.37×10^{-13}	1.68×10^{-11}	4.22×10^{-11}
Ionizing radiation, human health, IR-HH	Bq C-14 eq	3.58×10^{-12}	3.81×10^{-12}	9.06×10^{-13}	1.45×10^{-12}	1.52×10^{-13}	5.97×10^{-12}	2.05×10^{-13}	1.61×10^{-11}
Ozone layer depletion, OLD	kg CFC-11 eq	1.15×10^{-13}	6.68×10^{-14}	2.51×10^{-14}	3.64×10^{-13}	2.30×10^{-14}	4.91×10^{-13}	3.33×10^{-14}	1.12×10^{-12}
Human toxicity cancer, short term, HTC	CTUh	1.30×10^{-10}	4.56×10^{-11}	4.86×10^{-11}	3.69×10^{-11}	1.35×10^{-11}	2.76×10^{-9}	-1.07×10^{-11}	3.02×10^{-9}
Human toxicity cancer, short-term HT-NC	CTUh	2.06×10^{-10}	4.45×10^{-11}	3.40×10^{-11}	3.91×10^{-11}	7.75×10^{-12}	1.14×10^{-9}	-1.77×10^{-12}	1.47×10^{-9}
Particulate matter formation PMF	kg PM2.5 eq	5.31×10^{-10}	1.13×10^{-10}	1.69×10^{-10}	1.87×10^{-10}	5.82×10^{-11}	3.22×10^{-9}	4.25×10^{-10}	4.7×10^{-9}
Water availability, human health, WA-HH	m ³ consumed	4.46×10^{-10}	1.34×10^{-9}	6.69×10^{-11}	3.43×10^{-10}	2.80×10^{-12}	1.06×10^{-8}	6.84×10^{-11}	1.29×10^{-8}
Climate change, quality of ecosystems, in short CC-EQ	kg CO2 eq	1.33×10^{-4}	5.64×10^{-5}	4.48×10^{-5}	1.22×10^{-4}	3.13×10^{-5}	7.97×10^{-4}	1.58×10^{-5}	1.2×10^{-3}
Marine acidification, short term, MA	kg SO ₂ eq	1.04×10^{-5}	4.88×10^{-6}	3.61×10^{-6}	1.04×10^{-5}	2.82×10^{-6}	6.79×10^{-5}	1.60×10^{-6}	1.02×10^{-4}
Freshwater ecotoxicity, short term, FE	CTUe	1.44×10^{-5}	1.98×10^{-6}	6.22×10^{-6}	4.45×10^{-6}	1.94×10^{-6}	5.22×10^{-5}	2.91×10^{-7}	8.15×10^{-5}
Freshwater acidification, FA	kg SO ₂ eq	8.19×10^{-6}	2.50×10^{-6}	1.93×10^{-6}	4.46×10^{-6}	1.24×10^{-6}	6.30×10^{-5}	4.53×10^{-4}	5.34×10^{-4}
Terrestrial acidification, TA	kg SO ₂ eq	6.84×10^{-5}	1.61×10^{-5}	1.29×10^{-5}	2.88×10^{-5}	9.31×10^{-6}	3.99×10^{-4}	3.36×10^{-3}	3.89×10^{-3}
Freshwater eutrophication, FEU	kg PO ₄ P-lim eq	3.13×10^{-7}	2.99×10^{-8}	1.26×10^{-8}	5.77×10^{-8}	3.97×10^{-8}	3.16×10^{-7}	-2.09×10^{-7}	6.73×10^{-7}
Marine eutrophication, ME	kg N N-lim eq	2.25×10^{-6}	2.42×10^{-7}	3.26×10^{-7}	3.39×10^{-7}	2.83×10^{-7}	3.42×10^{-6}	-7.27×10^{-8}	6.79×10^{-6}
Ionizing radiation, ecosystem quality, IR-EQ	Bq C-14 eq	2.43×10^{-13}	2.94×10^{-13}	1.26×10^{-13}	1.00×10^{-13}	2.41×10^{-14}	5.25×10^{-13}	3.90×10^{-15}	1.32×10^{-12}
Land transformation, biodiversity, LT	m ² arable land	3.42×10^{-5}	8.88×10^{-6}	3.44×10^{-4}	2.16×10^{-5}	6.11×10^{-6}	1.28×10^{-4}	1.93×10^{-7}	5.43×10^{-4}
Land occupation, biodiversity, LO	m ² arable land x yr	1.76×10^{-4}	1.02×10^{-5}	1.90×10^{-4}	7.44×10^{-6}	2.16×10^{-6}	3.56×10^{-5}	-2.29×10^{-5}	3.99×10^{-4}
Water availability, freshwater ecosystem., WA-FE	m ³ dissipated	3.55×10^{-9}	7.15×10^{-9}	1.13×10^{-8}	3.04×10^{-9}	6.14×10^{-11}	5.25×10^{-8}	5.19×10^{-10}	7.81×10^{-8}
Water availability, terrestrial ecosystem., WA-TE	m ³ dissipated	7.84×10^{-8}	1.56×10^{-8}	6.61×10^{-9}	3.28×10^{-8}	8.61×10^{-10}	9.44×10^{-8}	4.2×10^{-10}	2.33×10^{-7}
Thermally polluted water, TPW	m ³ cooling water	2.84×10^{-9}	3.93×10^{-9}	7.13×10^{-10}	1.70×10^{-9}	4.00×10^{-11}	1.27×10^{-8}	3.23×10^{-10}	2.22×10^{-8}

Table 23
Numerical values of normalization for the home-compost (HC) biopolymer capsule

Categories of damage	Units	Production of HC granulates	Extrusion	Molding	Decontamination	Transport	Secondary packaging	End of life
Human health, HH	DALY	5.57×10^{-8}	3.71×10^{-8}	1.63×10^{-8}	4.15×10^{-8}	9.99×10^{-9}	4.71×10^{-7}	1.15×10^{-8}
Ecosystem quality, EQ	PDF.m ² . year	8.41×10^{-7}	2.36×10^{-7}	2.76×10^{-7}	2.51×10^{-7}	3.64×10^{-8}	9.85×10^{-6}	3.95×10^{-7}

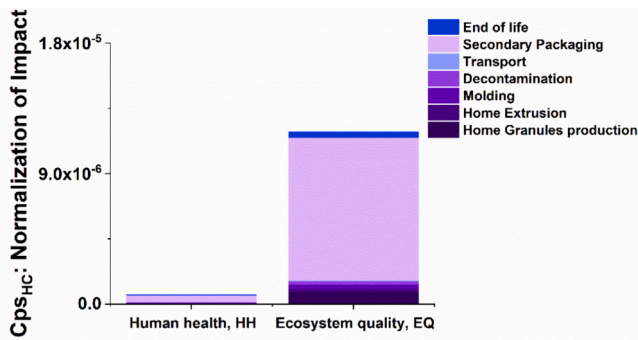


Fig. 11. Normalization of home-compost biopolymer capsule (Cps_{HC}) impacts.

confirmed considering the worst-case scenario with a reduction of 23.2 % and 36.4 %. In [Bishop et al. \(2021\)](#) land use and its variations are carefully examined, highlighting a crucial aspect in relation to the impacts of bioplastics resulting from agricultural raw materials. Although these raw materials are renewable in nature, it is important to consider their impact on land use, which could interfere with other functions and destinations of land use. Furthermore, the carbon neutrality hypothesis is generally considered valid in LCA studies, as carbon storage can potentially generate subsequent carbon emissions.

Also in Mastrolia et al. (2022) several life cycle assessments from cradle to grave on bioplastic materials were analyzed. Recycling of such materials is not a viable solution due to the high energy consumption and high cost of chemicals. Composting, on the other hand, does not produce high quality products, as the necessary pressure and temperature conditions are reproducible only in laboratory conditions. Therefore, fossil plastics of recycled origin can be seen as viable alternatives to bioplastics.

4.9. Economic circularity indices and multi-criteria decision analysis

4.9.1. Material circularity indicator, material reutilization score and multi-decision analysis results

The circularity indices are calculated based on the three disposal scenarios that are herein investigated. In the current disposal scenario, the raw material involved in the manufacturing of the capsule is virgin, with no secondary raw materials being involved. The recycling rate of the capsule at end-of-life is, instead, 80 %, while the percentage of

aluminum recovered at the end-of-life of the capsules is 67 %. The MCI value is, therefore, 0.35, which is a relatively low value. As far as MRS is concerned, the secondary raw materials involved in the manufacturing of the capsules is equal to zero, while the quantity of raw material recycled after the first use is equal to 100 %, therefore the MRS is equal to 66.67. MRS is also calculated for the capsules made from polypropylene and bioplastics. The polypropylene in the current disposable scenario has an MCI of 0.31, considering a recycling rate of 45 % and a recycling process efficiency of 80 %. Home compost and industrial compost bioplastics have an MCI equal to 0.33, thanks to a recycling rate of 10 %, a reuse of the material after use of 46 % and recycling efficiency of 80 %. Capsules in biopolymers, regardless of the type of composting, are, therefore, slightly closer to a circular model rather than capsules in polypropylene. In the 2033 (ten years) disposal scenario, for the case of capsules in both the bioplastics herein considered, it is set a 61 % reuse rate and a 6 % recycling rate after use. This causes an increase in the MCI to 0.4. An increase in recycling rate is also considered in the case of aluminum and polypropylene capsules. Despite this, in both cases, the calculated MCI for both aluminum and polypropylene is still lower with values of 0.39 and 0.31, respectively. In the second disposal scenario, MRS, as neither the recycled content nor the percentage of recyclable material changed after the first use, does not change if compared to the initial disposal scenario. In the third and last disposal scenario, the secondary raw material content is drastically changed in the manufacturing of aluminum and polypropylene capsule. This hypothesis is found to affect significantly both MRS and MCI. For both aluminum and polypropylene capsule, the MRS is 100, while for biopolymers this index does not change, since the last disposal scenario does not affect them. MCI for aluminum and polypropylene capsules in the third and last disposal scenario are 0.81 and 0.73, respectively. This is a clear improvement if these values are compared to the aforementioned current disposal scenario and the 2033 disposal scenario. In the last scenario, the MCI found for both polypropylene and aluminum capsules are rather close to the unit and, therefore, very close to represent a circular model. For the capsules made in home compost and industrial bioplastics, there are no changes if the third disposal scenario is considered, as it does not affect their life cycle. Based on the results, capsules in bioplastics, that can boast high composting rates, are more circular than capsule in aluminum and fossil plastics according to the 2033 disposal scenario. However, if aluminum and polypropylene capsules are entirely recycled after usage, they become very close to represent an ideal circular model. [Table 26](#) shows the results of the indicators for the current

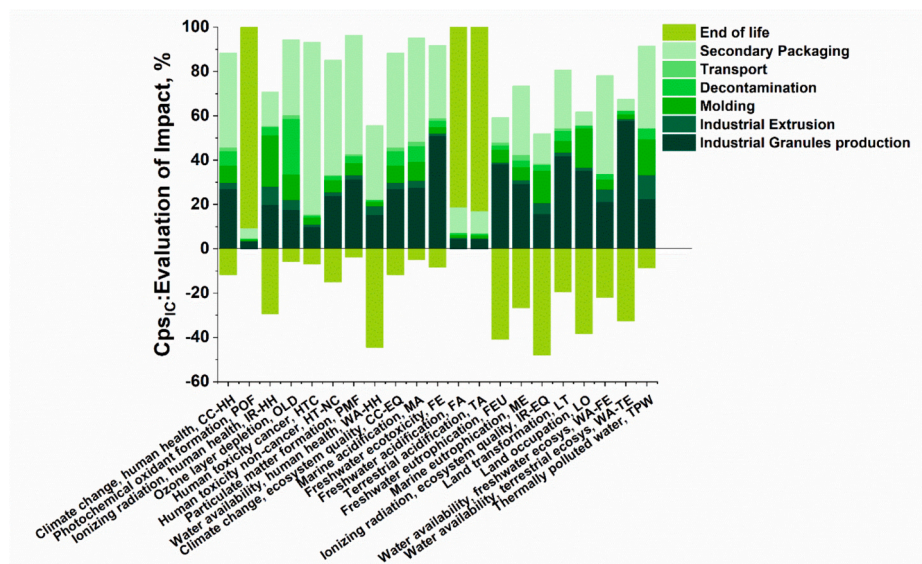


Fig. 12. Evaluation of industrial compost biopolymer (Cps_{IC}) capsule impacts.

Table 24
Numerical values of impact characterization for industrial compost (IC) biopolymer capsule

Impact categories	Units	Granule production IC	IC extrusion	Molding	Decontamination	Transport	Secondary packaging	End of life	Total
Climate change, human health, short term, CC-HH	kg CO2 eq	8.80×10^{-9}	2.75×10^{-10}	1.42×10^{-10}	5.65×10^{-10}	2.67×10^{-10}	1.68×10^{-10}	-1.5×10^{-10}	1.01×10^{-8}
Photochemical oxidant formation, POF	kg NMVOC eq	1.11×10^{-12}	2.8×10^{-14}	2.49×10^{-14}	5.24×10^{-14}	9.43×10^{-14}	3.59×10^{-13}	1.72×10^{-10}	1.74×10^{-10}
Ionizing radiation, human health, IR-HH	Bq C-14 eq	1.25×10^{-11}	3.43×10^{-12}	8.26×10^{-13}	1.45×10^{-12}	1.6×10^{-13}	4.04×10^{-11}	-1.1×10^{-12}	5.77×10^{-11}
Ozone layer depletion, OLD	kg CFC-11 eq	2.64×10^{-12}	7.09×10^{-14}	2.15×10^{-14}	3.64×10^{-13}	2.36×10^{-14}	1.40×10^{-12}	-2.7×10^{-13}	4.25×10^{-12}
Human toxicity cancer, short term, HTC	CTUh	3.03×10^{-9}	4.04×10^{-11}	3.85×10^{-11}	3.69×10^{-11}	1.39×10^{-11}	2.15×10^{-14}	-2.1×10^{-10}	2.95×10^{-9}
Human toxicity cancer, short-term HT-NC	CTUh	1.31×10^{-9}	4.49×10^{-11}	2.65×10^{-11}	3.91×10^{-11}	9.17×10^{-12}	1.19×10^{-13}	-1.2×10^{-10}	1.31×10^{-9}
Particulate matter formation PMF	kg PM2.5 eq	5.00×10^{-9}	1.15×10^{-10}	1.34×10^{-10}	1.87×10^{-10}	8.34×10^{-11}	7.37×10^{-9}	3.95×10^{-9}	1.68×10^{-8}
Water availability, human health, WA-HH	m ³ consumed	1.17×10^{-9}	1.38×10^{-9}	-1.7×10^{-11}	3.43×10^{-10}	-2.2×10^{-13}	1.34×10^{-10}	-4.2×10^{-11}	1.19×10^{-7}
Climate change, quality of ecosystems, in short CC-EQ	kg CO2 eq	1.90×10^{-3}	5.94×10^{-5}	3.08×10^{-5}	1.22×10^{-4}	5.79×10^{-5}	2.64×10^{-12}	-3.3×10^{-5}	2.14×10^{-3}
Marine acidification, short term, MA	kg SO ₂ eq	1.61×10^{-4}	5.15×10^{-6}	2.53×10^{-6}	1.04×10^{-5}	5.19×10^{-6}	4.49×10^{-11}	-2.2×10^{-6}	1.82×10^{-4}
Freshwater ecotoxicity, short term, FE	CTUe	7.75×10^{-5}	1.94×10^{-6}	5.19×10^{-6}	4.45×10^{-6}	2.53×10^{-6}	2.6×10^{-11}	-1.1×10^{-5}	8.06×10^{-5}
Freshwater acidification, FA	kg SO ₂ eq	9.64×10^{-5}	2.61×10^{-6}	1.4×10^{-6}	4.46×10^{-6}	2.32×10^{-6}	1.15×10^{-12}	4.6×10^{-3}	4.71×10^3
Terrestrial acidification, TA	kg SO ₂ eq	6.13×10^{-4}	1.68×10^{-5}	9.43×10^{-6}	2.88×10^{-5}	1.78×10^{-5}	1.34×10^{-10}	3.44×10^{-2}	3.51×10^{-2}
Freshwater eutrophication, FEU	kg PO ₄ P-lim eq	9.18×10^{-7}	2.48×10^{-8}	1.2×10^{-7}	5.77×10^{-8}	4.04×10^{-8}	8.26×10^{-13}	-2.4×10^{-6}	-1.24×10^{-6}
Marine eutrophication, ME	kg N N-lim eq	5.64×10^{-6}	2.16×10^{-7}	2.61×10^{-7}	3.39×10^{-7}	5.77×10^{-7}	1.19×10^{-13}	-1.6×10^{-6}	5.43×10^{-6}
Ionizing radiation, ecosystem quality, IR-EQ	Bq C-14 eq	1.15×10^{-12}	2.09×10^{-13}	1.19×10^{-13}	1×10^{-13}	2.61×10^{-14}	2.65×10^{-11}	-2.1×10^{-13}	2.79×10^{-11}
Land transformation, biodiversity, LT	m ² arable land	2.39×10^{-4}	9.1×10^{-6}	3.42×10^{-4}	2.16×10^{-5}	6.11×10^{-6}	1.59×10^{-5}	-6.2×10^{-5}	5.72×10^{-4}
Land occupation, biodiversity, LO	m ² arable land x yr	6.27×10^{-5}	9.21×10^{-6}	1.82×10^{-4}	7.44×10^{-6}	2.16×10^{-6}	1.13×10^{-5}	-6.4×10^{-5}	2.11×10^{-4}
Water availability, freshwater ecosystem., WA-FE	m ³ dissipated	5.42×10^{-7}	7.37×10^{-9}	3.65×10^{-7}	3.04×10^{-9}	6.61×10^{-11}	5.58×10^{-9}	-1.3×10^{-9}	9.22×10^{-7}
Water availability, terrestrial ecosystem., WA-TE	m ³ dissipated	1.46×10^{-7}	1.66×10^{-8}	5.58×10^{-9}	3.28×10^{-8}	8.61×10^{-10}	7.98×10^{-8}	-2.7×10^{-8}	2.55×10^{-7}
Thermally polluted water, TPW	m ³ cooling water	7.98×10^{-8}	4.05×10^{-9}	1.23×10^{-8}	1.7×10^{-9}	4×10^{-11}	7.09×10^{-14}	-3.3×10^{-10}	2.08×10^{-7}

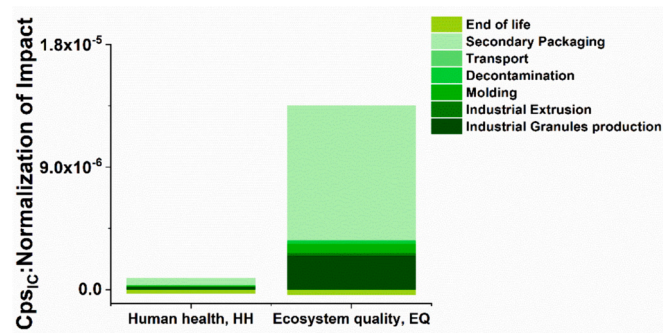


Fig. 13. Normalization of industrial compost biopolymer (Cps_{IC}) capsule impacts.

disposal scenario. The best alternative is highlighted in green, the intermediate alternative in yellow and the best one in green. The results show that the best technological alternatives are represented by the two home and industrial compost bioplastics. Table 27 shows the results of the MCDA analysis for the current disposal scenario, once again exploiting the color scale used for the indicators.

The home compost capsule presents itself as the best technological alternative for three out of five scenarios, respectively S2, S3 and S4, while industrial compost capsule provides better results only in S5. The polypropylene capsule, on the other hand, appears to be the worst technological alternative for all scenarios.

For the 2033 (ten years) disposal scenario, the results of the analysis of the indices and MCDA are reported in Tables 28 and 29, respectively. These results confirm what was previously seen in the current scenario, improving the MCI index for bioplastics and, thus, resulting in an

improvement of circularity. For the polypropylene capsule the situation remains almost unchanged, while for the aluminum one there is a deterioration in performance due to the MCI value which is lower than that of bioplastics. Even for the MCDA analysis, no particular changes are highlighted, confirming the advantage of bioplastics compared to fossil materials.

Tables 30 and 31 show the results of the indices and the MCDA analysis. Considering for materials of fossil origin (i.e., both aluminum and polypropylene), 100 % recycled raw material, the scenario changes significantly, highlighting how the use of recycled polypropylene comes closer to a circular economy model compared to bioplastics. Aluminum improves its performance but turns out to be the worst alternative in three scenarios: S1, S3 and S5.

If 100 % recycled, the polypropylene capsule represents the best technological alternative in all scenarios, while bioplastics represent the worst alternative for S2 and S4. Therefore, the presence of recycled raw material, in addition to reducing damage to human health and the quality of the ecosystem as already highlighted in the LCA analysis, improves the circularity of the material as demonstrated by MCDA analysis.

A limitation of such research can be seen in the lack of a cost analysis, to obtain an economic evaluation of the product, not only from the environmental point of view. The inclusion of this analysis could add value to future research in the field.

5. Conclusions

In the present study, the possibility of replacing coffee capsules manufactured from materials of fossil origin, such as aluminum and polypropylene, with biocompostable plastics is investigated. Through LCA analysis, it is highlighted that bioplastics are currently more

Table 25
Numerical values of normalization for industrial compost (IC) biopolymer capsule

Categories of damage	Units	Production of IC granulates	Extrusion	Molding	Decontamination	Transport	Secondary packaging	End of life
Human health, HH	DALY	2.43×10^{-7}	3.57×10^{-8}	5.48×10^{-8}	4.15×10^{-8}	9.99×10^{-9}	4.71×10^{-7}	-2.48×10^{-7}
Ecosystem quality, EQ	PDF.m ² . year	2.51×10^{-6}	2.22×10^{-7}	6.31×10^{-7}	2.51×10^{-7}	3.64×10^{-8}	9.85×10^{-6}	-3.34×10^{-7}

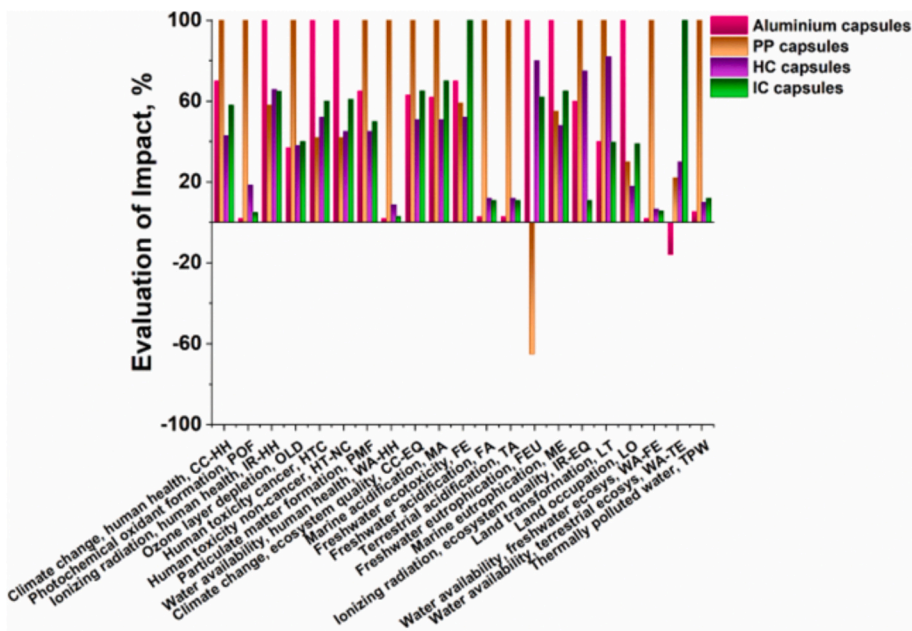


Fig. 14. Evaluation of the impacts of the current disposal scenario for aluminum, polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule.

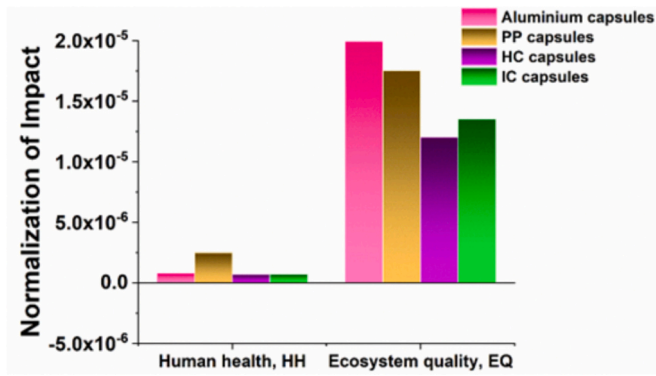


Fig. 15. Normalization of the impacts of the current disposal scenario for aluminum, polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule.

sustainable, in particular when they are disposed of through domestic composting, which has less impact on the environment, as the use of an industrial composting plant is not necessary. Polypropylene, on the other hand, represents the most impactful alternative from both an environmental and human health point of view. In the ten years disposal scenario, based on the directives dictated by the European Union, bioplastics maintain their primacy, increasing the gap with the both the fossil materials. Considering an extreme disposal scenario in which aluminum and polypropylene are 100 % recycled, capsules produced from polypropylene would be more environmentally friendly than bioplastics. The aluminum capsule continues to be uncompetitive from an environmental point of view. MCDA, carried out both on the current and ten years disposal scenario, confirms the results obtained by LCA. In the ten years disposal scenario, capsules made from 100 % recycled polypropylene show a more interesting ecological profile, demonstrating high circularity. This is underlined not only by LCA indicators, but also in terms of circularity indices, highlighting the high circularity of recycled polypropylene.

This study highlights how bio-based plastics currently represent a solid alternative to fossil materials, such as aluminum and polypropylene, to produce coffee capsules. The adoption of method 0/0 and therefore of carbon neutrality seems to give good results for the impacts

related to bioplastics. Disposal processes such as incineration and recycling have environmental benefits, including the management of multifunctionality and the subtraction of avoided products. The same can be said for composting.

However, bioplastics has intrinsically some limits, mainly linked to the exploitation of the territory and the ecosystem, deriving from intensive cultivation and the use of chemical herbicides. Other limitations are related to the disposal of bioplastics. Composting is seen as the most appropriate disposal for this type of material, but at the same time requires temperature and humidity conditions that are not easily reproducible.

As a result, materials with a recycled component or entire composition emerge as a promising option to mitigate the environmental impacts arising both from the extraction of mineral and fossil resources, and from those that affect the quality of the ecosystem. It should be noted that recycled materials still have limits in the number of recycling cycles that can be achieved. For example, polypropylene can be subjected to three recycling cycles, unlike aluminum, which can be recycled virtually unlimited.

In addition, future research should focus on this aspect not only for

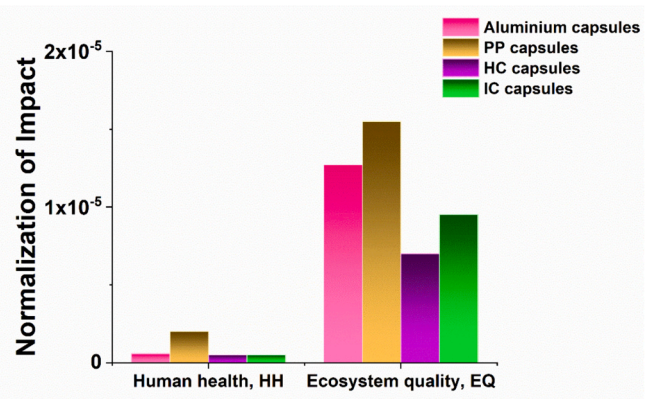


Fig. 17. Normalization of the impacts of the future disposal scenario for aluminum, polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule.

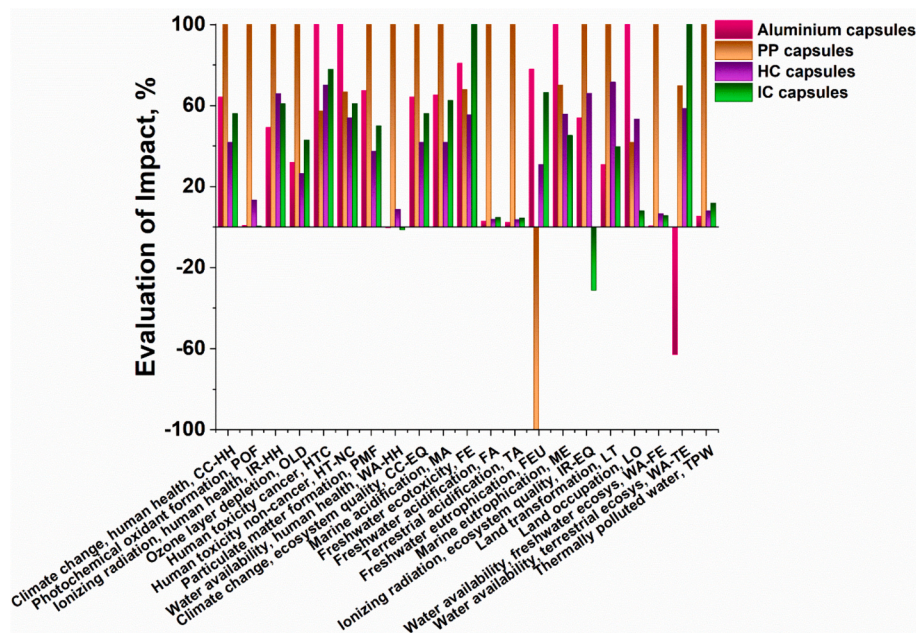


Fig. 16. Assessment of the impacts of the future disposal scenario for aluminum, polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule.

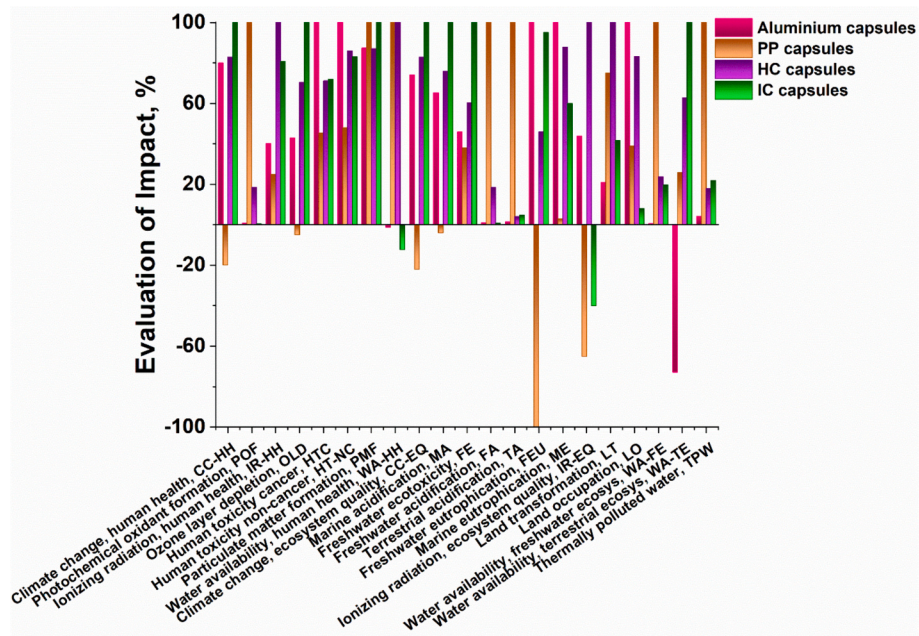


Fig. 18. Evaluation of the impacts of the future disposal scenario with aluminum and recycled polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule.

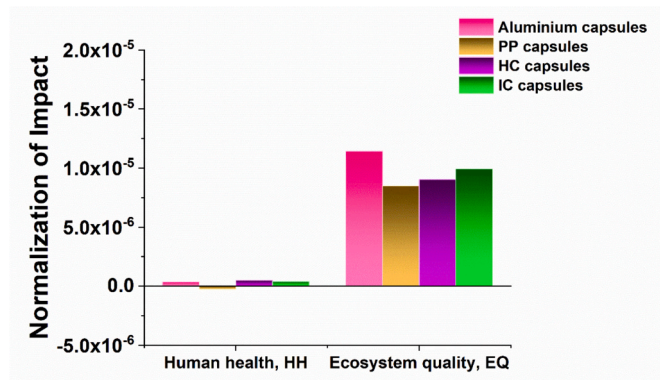


Fig. 19. Normalizing the impacts of the future disposal scenario with aluminum and recycled polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule.

Table 26
Indicative results of the current scenario for Aluminum, Polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule (cps)

Packaging identifier	Cps in aluminum	PP cps	HC cps	IC cps
Material Reutilization Score [-]	66.67	66.67	66.67	66.67
Material Circularity Indicator [-]	0.35	0.27	0.33	0.33
Human Health [DALY]	7.08×10^{-7}	2.65×10^{-6}	6.44×10^{-7}	6.09×10^{-7}
Ecosystem quality [PDFxm ² year]	2.17×10^{-3}	1.72×10^{-3}	1.19×10^{-3}	1.32×10^{-3}

coffee capsules, but also for other types of food packaging.

CRedit authorship contribution statement

Maria Pia Desole: Writing – review & editing, Writing – original draft, Software. **Annamaria Gisario:** Writing – review & editing, Writing – original draft, Validation. **Massimiliano Barletta:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Table 27
Current scenario Multi-Criteria Decision Analysis results for Aluminum, Polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule (cps)

Scenario	S1	S2	S3	S4	S5
	Point	Point	Point	Point	Point
Packaging					
Cps in aluminum	0.953	0.713	0.695	0.693	0.84
PP cps	1.2×10^{-3}	0.147	0.156	0.157	0.073
HC cps	0.887	0.840	0.926	0.953	0.889
IC cps	0.890	0.835	0.914	0.934	0.889

Table 28
Results of future scenario indicators for Aluminum, Polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule (cps)

Packaging identifier	Cps in aluminum	PP cps	HC cps	IC cps
Material Reutilization Score [-]	66.67	66.67	66.67	66.67
Material Circularity Indicator [-]	0.39	0.31	0.4	0.4
Human Health [DALY]	5.06×10^{-7}	2.06×10^{-6}	4.27×10^{-7}	3.97×10^{-7}
Ecosystem quality [PDFxm ² year]	1.63×10^{-3}	1.34×10^{-3}	7.90×10^{-4}	9.92×10^{-4}

Table 29
Multi-Criteria Decision Analysis results future scenario for Aluminum, Polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule (cps)

Scenario	S1	S2	S3	S4	S5
	Point	Point	Point	Point	Point
Packaging					
Cps in aluminum	0.936	0.145	0.674	0.672	0.824
PP cps	0	0.030	0.130	0.131	0.061
HC cps	0.920	0.166	0.948	0.966	0.921
IC cps	0.923	0.163	0.896	0.903	0.914

Table 30

Indicative results of the future scenario with recycled aluminum and polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule (cps)

Packaging identifier	Cps in aluminum	PP cps	HC cps	IC cps
Material Reutilization Score [-]	100	100	66.67	66.67
Material Circularity Indicator [-]	0.81	0.73	4.00 x10 ⁻¹	0.4
Human Health [DALY]	3.54x10 ⁻⁷	-2.55 x10 ⁻⁷	4.88 x10 ⁻⁷	3.97 x10 ⁻⁷
Ecosystem quality [PDFxm ² year]	1.143x10 ⁻⁵	8.49 x10 ⁻⁶	9.03 x10 ⁻⁶	9.92 x10 ⁻⁶

Table 31

Multi-Criteria Decision Analysis results future scenario with recycled aluminum and polypropylene (PP), Home Compost (HC) and Industrial Compost (IC) capsule (cps)

Scenario	S1	S2	S3	S4	S5
	Point	Point	Point	Point	Point
Packaging					
Cps in aluminum	3.712 x10 ⁻¹³	0.233	0.051	0.224	0.075
PP cps	1	0.233	0.949	0.974	0.925
HC cps	0.395	0.207	0.235	0.111	0.267
IC cps	0.259	0.032	0.213	0.140	0.266

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2024.05.003>.

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